Advanced Life Support Power Reduction
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Abstract

The proposed Advanced Life Support Power Reduction research will develop approaches for reducing system power and energy usage in Advanced Life Support (ALS) regenerative systems suitable for exploring the Moon and Mars. The effects of system configuration and processor scheduling will be investigated, along with system energy integration and energy reuse techniques and advanced control methods for efficient distribution of power and thermal resources. The results of this effort will be instrumental in guiding the design of future life support systems. The ALS Systems Integrated Test Bed at the NASA Johnson Space Center will serve as a baseline for these studies.

Although advanced life support systems offer significant benefits for future long-duration human exploration missions, the high power requirement associated with food production and overall closed regenerative system operation remains as a critical technological challenge. Optimization of individual processors alone will not be sufficient to produce an optimized system. System studies must be used in order to improve the overall efficiency of life support systems.

The development of a complete system design that reuses waste heat from sources such as crop lighting and solid waste processing systems will have a major impact on the reduction of system power requirements, thus reducing the equivalent system mass. Waste heat can be reused by processors such as an Air Evaporation Unit, which is used for water processing, as well as for food processing, food preparation, or heating of shower water, dish wash water, or clothes wash water. The use of state-of-the-art control methods for distribution of resources, such as system cooling water or electrical power, will also reduce system power requirements. This type of applied research is implemented regularly by industry in order to design more efficient systems that are less costly to operate.

The proposed work will be based on past and current research at Ames Research Center. The energy balance models will leverage off of existing mass flow models of regenerative life support systems developed at Ames Research Center. The new power saving approaches resulting from this work will be provided to Johnson Space Center for use in the development of the ALS Systems Integrated Test Bed and in the design of flight hardware for Moon or Mars missions.

Task Progress

Currently, designs are being developed that match sources of waste heat, such as crop lighting and solid waste processing systems, with processes that can use this waste heat, such as water processing, food processing, food preparation, and heating of shower water, dish wash water or clothes wash water. Using energy integration techniques, optimal system heat exchange designs are being developed by matching hot and cold streams according to specific design principles. For various designs, the potential savings for power, heating and cooling are being identified and quantified, and estimates are being made on the emplaced mass needed for energy exchange equipment.

The goal for the first year is to develop thermally-integrated system designs using the ALS Systems Integrated Test Bed at JSC (also known as BIO-Plex) as a baseline system. This involves identifying candidate technologies and designs for the BIO-Plex and evaluating the energy exchange potential of the available hot and cold streams associated with each technology. An example BIO-Plex system design has been selected for application of the proposed analysis. Steady-state flows through the system have been determined, and temperature intervals, heat capacities and heat duties for flowrates of interest have been developed. A spreadsheet has been developed which contains information compiled from various sources on thermal flow characteristics of candidate BIO-Plex technologies. The final step involves identifying and quantifying potential savings for power, heating and cooling, and making estimates of the increase in emplaced mass needed for energy exchange equipment.

Details of the work completed towards a thermally-integrated system can be found in the enclosed report's first section, entitled "Application of the Pinch Technique to an Advanced Life Support System with Partial Food Production and Partial Waste Recycling Under Steady-State Conditions."

In addition to the energy integration work, advanced control system designs are being developed that allow for more efficient distribution of resources, such as system cooling water or electrical power, in order to reduce system power requirements. More efficient energy usage can be achieved by allocating power and thermal resources in a dynamic fashion. Advanced control techniques, such as market-based control, can be used in order to smooth out system thermal and power loads. Reductions in the peak loading will lead to lower overall requirements. The controller dynamically adjusts the use of system resources by the various subsystems and components in order to achieve the overall system goals. A typical system goal would be the smoothing of power usage and/or heat rejection profiles, while maintaining adequate reserves of food, water, oxygen, etc., and not allowing excessive build-up of waste materials. Initially, computer simulation models are being used to test various control system designs. The most promising of these will be tested using a laboratory-scale life support system testbed at Ames Research Center.

First year tasks include identifying a set of resource allocation objectives for an example regenerative life support system, developing a simulation model of an example subsystem, and developing a controller to satisfy the resource allocation objectives for the target subsystem. Progress has been made on all three tasks. The BIO-Plex is taken as a baseline system. The resource allocation objective is to smooth the demand for power throughout the system while meeting a tolerance constraint on mass resources. The tolerance constraint provides us with the ability to decrease power to certain processes when necessary in order to smooth the overall system power usage, while maintaining adequate life support function. A dynamic model of the BIO-Plex air loop has been created and serves as a platform for the development of active power management strategies. A power management system has been implemented. A central controller uses processor tolerances and current power capacity to re-allocate energy when a power surge is detected. Future work will build on the current architecture, and will include decentralized management strategies, such as market-based control.

Details of the work completed in the area of power distribution can be found in the enclosed report's second section, entitled "A Power Allocation Strategy Applied to a Regenerative Life Support Sub-System."

Application of the Pinch Technique to an Advanced Life Support System with Partial Food Production and Partial Waste Recycling Under Steady-State Conditions

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1 Introduction

The systems modeling and analysis group at Ames Research Center is currently working on the first year tasks for the grant entitled "Advanced Life Support Power Reduction." The Advanced Life Support Power Reduction research involves developing approaches for reducing system power and energy usage in Advanced Life Support (ALS) regenerative systems suitable for exploring the Moon and Mars. The effects of system configuration and processor scheduling are being investigated; along with system energy integration and energy reuse techniques and advanced control methods for efficient distribution of power and thermal resources. Here we discuss progress to date on applying system energy integration and energy reuse techniques to the life support problem.

1.1 Approach

One of the main objectives of the power reduction research is to develop system designs that are more efficiently integrated from an energy standpoint, so that the equivalent system mass of future life support systems can be reduced. Hot and cold streams within the system can be matched and their energy exchanged in order to lower the external cooling and heating requirements. Some subsystem designers have taken advantage of energy integration within their subsystem design in order to minimize power usage. However, due to limitations on the number of available hot and cold streams within a given subsystem, only partial energy reuse is generally achievable. A system approach to energy integration will inevitably yield better results than the more common subsystem-by-subsystem power optimization approach. When the entire system is treated, there is much more flexibility in the design approach, and the potential for energy reuse is substantially greater.

In *A User Guide on Process Integration for the Efficient Use of Energy* by B. Linnhoff, energy integration techniques are discussed. Using the simple, practical method outlined in Linnhoff's book, referred to here as the “Pinch Technique”, system design options can be identified that lower the overall system energy usage. In the Pinch Technique, first, process streams and their thermal attributes (heat capacity flowrate, supply temperature and target temperature) are identified. The heat duty that is required to bring each stream from its supply temperature to its target temperature is calculated. Next, composite curves are constructed, first for the streams that require cooling (hot streams), then for the streams that require heating (cold streams). The hot composite curve contains the aggregate energy content information for all of the hot streams, and the cold composite curve contains all of the aggregate energy content information for all of the cold streams.

The hot and cold composite streams are plotted together in a heat content graph, and the minimum heating and cooling requirements for the system are identified. An energy cascade (a net enthalpy balance on the system) is performed to identify the locations where external heating and cooling must be supplied. Once the energy cascade has been completed, matching hot and cold streams such that heat exchanger loads are maximized, so that the total number of exchangers can be minimized, can develop an optimal system heat exchange design.

1.2 Year One Goals and Tasks

The goal for year one of the energy integration work is to develop thermally integrated system designs using the BIO-Plex as a baseline system. Specific tasks for the first year include:

1. Identify candidate technologies and designs for the BIO-Plex.
2. Identify potential hot and cold streams for candidate technologies.
3. Develop energy content data for each hot and cold stream using mass and energy flow models as needed to produce temperature, flow and composition data.
4. For various candidate designs, identify and quantify potential savings for power, heating and cooling, and make estimates on the increase in emplaced mass needed for energy exchange equipment.
5. Make recommendations on system designs that incorporate energy reuse.
6. Prepare a report and/or research paper to document the results listed above.

1.3 Current Status

A spreadsheet containing information compiled from various sources on thermal flow characteristics of candidate BIO-Plex technologies has been developed. From this spreadsheet and discussions with ALS researchers, an example subsystem for application of the Pinch Technique has been developed. Steady-state flows through the system have been determined, and resultant temperature intervals, heat capacities and heat duties for flowrates have been calculated. A temperature interval analysis has been performed, and the related heat cascade has been generated. From the generated heat cascade, a Pinch analysis was performed to develop a design for achieving the minimum amounts of external heating and cooling for the example system. Heat exchanger networks were developed, and each heat exchanger was assessed for cost-effectiveness in terms of equivalent system mass (ESM). From the calculated savings in terms of ESM, mathematical relationships were estimated for the amount of savings in a Martian transit and surface stay as a function of heat exchanger heat duty.

2 Data Collection

The attached EXCEL spreadsheet contains information compiled from various sources on thermal flow characteristics of candidate BIO-Plex technologies. Different subsystems (atmosphere revitalization, water recovery, solids processing, biomass production, food processing and habitat) are separated by spreadsheet, as listed on the tab at the bottom of the spreadsheet frame. Within each subsystem, technologies are categorized according to function, as denoted by the gray tags to the leftmost edge of each sheet. Technologies within a function tag are further categorized as used in the LMLSTP Phase III Test Bed, planned for the ISS, candidate BIO-Plex technology, or ‘other technology’. A particular technology may be listed in a sheet more than once. For instance, Four-Bed Molecular Sieve is listed on the atmosphere revitalization sheet under the LMLSTP Phase III Test Bed as well as the ISS, with data representative of each location. The spreadsheet does not include data for every piece of electrical equipment planned for the BIO-Plex. The spreadsheet includes data only for equipment in which heating and/or cooling of flow streams may be required.

Data is displayed under several column headings (stream flowrate, stream composition, supply temperature, target temperature, etc.), and “notes” on a particular piece of information are occasionally included (denoted by a red triangle in the upper right corner of a cell). Notes can be viewed by holding the mouse directly over the cell of interest. The source of the information is listed under the “source” column, or in a cell note, when referring to one piece of information. The sources are described more completely under ‘References’ below. The columns of data that are included in the spreadsheet will allow for future calculation each stream’s heat duty.

The name of the process and the stream of interest are in the first two columns. Most technologies will have at least one inlet stream and one outlet stream, and some technologies have more than one inlet or outlet stream. Separate rows of data are listed for every stream of a process. Stream composition will be used to calculate stream heat capacities, which will be discussed in a later memo. The heat capacity of a stream is one of the properties required for calculating the heat duty.

Average stream flowrate is taken from the source document for the particular conditions in which the technology was utilized. The mode column delineates the flow as continuous, batch or semibatch. The column for the typical duration of use lists the amount of time for which a process is normally run in that mode. Streams in a system must be compatible in terms of mode and duration in order to be mixed for energy exchange.

The number of crew supported by the process at the given flowrate is mission and design dependent. For example, in the LMLSTP Phase III Test Bed, CO_2 reduction was performed with a Sabatier unit at a flowrate of approximately 0.2kg CO_2 per day. This processing rate is related to the amount of food that was grown, crew activity, incineration rates and other system attributes. In a system with different attributes, the processing rate for four crewmembers would be different. Because of this, all future scaling of equipment power requirements must be done with respect to flowrate, rather than number of crew supported by the processor.

For an inlet stream, the supply temperature is the temperature of a stream immediately preceding the process of interest, and the target temperature is the desired temperature of the stream during processing. For an outlet stream, the supply temperature is the temperature of the stream during processing, and the target temperature is the desired temperature of the stream immediately following processing. The heat source or heat sink used for bringing a stream to the target temperature denotes the potential amount and type of energy that could be saved if this stream were mixed with another hot or cold stream to reach the target temperature. Reducing the load on the HVAC system, reducing electrical heating requirements, or reducing cooling water requirements can save energy.

At the top of the biomass production spreadsheet, three possibilities are given for lamp intensity, depending on which of three ballast levels are utilized. Also at the top of the sheet, lamp and ballast cooling requirements are listed per lamp to enable calculation of heat loads for various lamp illumination combinations in a light box. In the bottom portion of the biomass production spreadsheet, calculations are shown for maximum cooling requirements for each crop tray, given full lamp intensity (400W) and all lamps on.

3 Description of the Example System

The Pinch Technique is typically applied to industrial designs that are already in existence or are substantially predefined. In this investigation, the BIO-Plex Phase I, 120-day test with a crew of four persons is used as a starting point for an initial investigation of applying the Pinch Technique to bioregenerative life support systems. The Phase I test will entail partial food production in one Biomass Production Chamber (BPC1) and 25% solids processing. Because the BIO-Plex is still in the design phase, assumptions on some technologies must be made in order to apply the technique. In the following sections, technology and design choices are defined, based on information obtained in the data collection efforts. Technologies were selected based upon probable technologies specified by BIO-Plex personnel, the availability of data as well as the potential enthalpy demand or supply of a particular technology.

3.1 Biomass Production Chamber

The crops that will be grown in BPC1 and possible growth parameters are listed in Table 1. It is assumed that 400W high-pressure sodium (HPS) lamps will be used throughout the chamber. It is also assumed that the lamp arrangement will be designed such that any crop may be grown in any tray and that crop-specific light intensities will be achieved by turning on a percentage of the available lamps. It is assumed that lamps will be air-cooled, with a Teflon barrier at the bottom of each light box.

The crop dryer will be used at harvest times to dry wheat berries and soybeans. Three to four uses per week during harvest are an initial guess on the frequency of use of the crop dryer[1]. However, for this document, it is assumed that the crop dryer feed and air flowrates are continuous and at steady state.

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[1] Peterson, Laurie, personal communication, June 1999.

Table 1. Possible crop growth specifications for BPC1.

Crop[2]	Number of Trays[3]	Area per Tray[2] (m^2)	Growth Period[4,] (d)	Photoperiod[4] (h)	PPF[4] ($\mu mols/m^2$-s)
Wheat	**1**	**14.17**	**74**	**24**	**1500**
Wheat	**2**	**3.35**	**74**	**24**	**1500**
Soybean	**3**	**14.17**	**90**	**12**	**1000**
Potato	**1**	**6.19**	**112**	**12**	**1000**
Sweet Potato	**1**	**6.19**	**120**	**12**	**1000**
Tomato	**1**	**3.35**	**85**	**16**	**1000**
Salad Mix	**1**	**3.35**	**45**	**16**	**350**

3.2 Food Processing and Preparation System

The unit in the food processing and preparation system (FPS) that is of most interest in terms of reusing waste heat in the Pinch Technique is the dishwasher. It is assumed that a dishwasher is used once daily to clean utensils, pots, pans and dishes.

3.3 Solids Processing System

A system similar to that which was used in the LMLSTP Phase III Test Bed is assumed to treat 25% of solid wastes in the first BIO-Plex test. Packaging is not included in the treated wastes.

The solids processing system (SPS) system will consist of a fluidized combustion unit, followed by a particulate filter, a catalytic gas cleanup system, and an activated carbon trace contaminant cleanup system[5]. Atypically small SPS processors will be assumed for this study for several reasons. Only a portion of the crew food is grown in BPC1, which limits the amount of inedible biomass that is oxidized in the SPS. Only 25% of the solid waste that is generated (inedible biomass, wasted edible biomass and human wastes) is treated in the SPS system, which further limits the loading to the SPS. Also, this initial application of the Pinch Technique considers steady-state conditions, thus spreading out over time the SPS loading and reducing the overall size. Upon applying the Pinch

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[2] Castillo, Juan. Personal communication, June 1999.

[3] Barta, Daniel J; Castillo, Juan M; Fortson, Russ E. The Biomass Production System for the Bioregenerative Planetary Life Support Systems Test Complex: Preliminary Designs and Considerations, 29th International Conference on Environmental Systems, SAE #1999-01-2188.

[4] Henderson, Keith. Personal communication, June 1999.

[5] Edeen, Marybeth; Pickering, Karen D. Biological and Physical-Chemical Life Support Systems Integration – Results of the Lunar Mars Life Support Phase III Test. 28th International Conference on Environmental Systems, SAE #981708, 1998.

Technique to systems with increased solid waste recycling, SPS processor sizes will increase. Dynamic variations in the processor loads will be considered in later studies and will also cause SPS processor sizes to increase.

3.4 Atmosphere Revitalization System

For CO_2 recovery, a four-bed molecular sieve (4BMS) is assumed, in which the incoming air is first passed over a desiccant bed and then passed through a CO_2 sorbent bed. The CO_2-lean air is then passed through a second desiccant bed that is in the desorption phase, so that water is added back to the revitalized air before returning to the atmosphere. A solid polymer water electrolysis system is used to generate O_2 and H_2 from water. Hydrogen gas is assumed to be vented.

The trace contaminant control system (TCCS) is assumed to be similar to that which was used in the LMLSTP Phase III Test Bed[6]. The first two units in the TCCS are an ammonia removal catalyst and an Englehard catalyst to oxidize hydrocarbons and oxygenates to CO_2 and H_2O. Ten percent of the airflow is then directed to another Englehard catalyst and heated to oxidize methane and halocarbons. The air is finally passed over a sorbent bed to remove hydrogen chloride and hydrogen fluoride formed during the oxidation of halocarbons.

3.5 Water Recovery System

The water recovery system (WRS) is assumed to consist of immobilized cell and trickling filter bioreactors, followed by reverse osmosis and an air evaporation system (AES), ammonia removal system and aqueous-phase catalytic oxidation system (APCOS). Such a system is similar to that used in the LMLSTP Phase III Test[7].

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[6] Brasseaux, Sandra F.; Graf, John C.; Lewis, John F.; Meyers, Karen E.; Rosenbaum, Melissa L.; Supra, Laura N. Performance of the Physicochemical Air Revitalization System During the Lunar-Mars Life Support Test Project Phase III Test. 28th International Conference on Environmental Systems, SAE #981703, 1998.

[7] Pickering, Karen D; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results. 28th International Conference on Environmental Systems, SAE #981707, 1998.

4 Determination of Steady-State Mass Flowrates

Steady-state flowrates of atmospheric gases, solid wastes, greywater, and edible biomass are estimated for the first planned BIO-Plex test. The estimates are made in order to determine the flow of streams that may require cooling and streams that may require heating for various technologies in the test bed.

In the first test, a crew of four will remain in the test bed for 120 days[8]. A “hot start” will be initiated, with plants at varying degrees of maturity in the first biomass production chamber. There will be stored agricultural products in bins ready for processing, biological water and waste processors fully inoculated at steady state and a steady-state heat load at the onset of the test. It is planned that BPC1 will supply a portion of the crew’s diet, and 25% of the solid waste will be recovered[9].

Separate plant/crew air loops will be incorporated for the first BIO-Plex test. In such a configuration, air from the crew compartment is cycled to the atmosphere revitalization system (ARS) for CO_2 removal and O_2 and N_2 addition. Air is then returned to the crew compartment. CO_2 that is removed is stored in a buffer tank until it is needed by BPC1. Air from BPC1 is sent directly to the ARS for O_2 scrubbing and CO_2 and N_2 addition. O_2 that is removed is stored in a buffer tank until needed by the crew or SPS. Crop transpiration water is treated in the WRS and recycled to nutrient tubs. Crew wastewater is treated in the WRS and recycled to the crew and ARS.

4.1 Biomass Production Chamber

The growth rates and compositions of edible and inedible biomass from BPC1 are required to determine rates of CO_2 consumption, H_2O consumption and O_2 production. The quantity of O_2 that is generated by the crops in BPC1 reduces the O_2 generation demand on the ARS. The quantity of edible biomass that is produced by the crops must be processed in the food processing system before being consumed by the crew. The inedible biomass and the wasted edible biomass produced by the crops must be sent to the SPS.

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[8] Tri, Terry O. BIO-Plex Project Status. Presented at the Advanced Life Support Status Meeting/Teleconference, May 20, 1999.

[9] Advanced Life Support Program Plan, Rev A, CTSD-ADV-348, JSC 39168, Crew and Thermal Systems Division, Lyndon B. Johnson Space Center, NASA, 1998, Section 8.0.

Table 2 shows typical edible crop compositions in terms of edible protein, fat, carbohydrate, fiber and water[10]. All dry, inedible biomass is assumed to consist of 35% protein, 50% fiber and 15% lignin by mass. Table 3 shows the water mass percentages for the inedible portion of crops grown in BPC1.

Table 4 shows the nominal production rates of wet and dry edible and inedible biomass, assuming nominal edible biomass growth rates from the Baseline Values and Assumptions Document (BVAD). (Note that tomato edible growth rate is taken from Drysdale et al, 1997). The overall crop harvest index is 0.27 kilograms of edible crop per kilogram of total biomass. It is assumed that 25% of the inedible biomass is sent to the SPS, and the vaporized inedible crop water is eventually sent to the WRS, for a water load of 23.98 kg/d.

It is assumed that crop transpirate is condensed, collected and sent to the WRS for processing. Table 5 shows possible transpiration rates for each crop and resultant loading to the WRS.

[10] For conventionally grown (not hydroponically-grown) crops.

Table 2. Typical Wet Edible Biomass Compositions, Excluding Minerals.[11]

Crop	Protein Mass Percent	Carbohydrate Mass Percent	Fat Mass Percent	Fiber Mass Percent	Water Mass Percent
Wheat	**11.9**	**62.1**	**2.0**	**10.5**	**13.4**
Soybean	**12.6**	**10.8**	**6.6**	**4.1**	**65.9**
Potato	**2.1**	**15.3**	**0.1**	**2.1**	**80.4**
Sweet Potato	**1.7**	**24.4**	**0.6**	**3.2**	**70.2**
Tomato	**1.0**	**2.6**	**0.2**	**1.0**	**95.2**
Mix[12]	**1.3**	**2.3**	**0.2**	**1.0**	**95.2**

Table 3. Inedible Biomass Water Mass Percent for BPC1 Crops.

Crop	Inedible Biomass Water Mass Percent[13]
Wheat	**91**
Soybean	**86**
Potato	**85**
Sweet Potato	**85**
Tomato	**95**
Mix[12]	**95**

[11] Scherz, Heimo; Senser, Friedrich. Food composition and Nutrition Tables, 5th edition, Scientific Publishers, Stuttgart, 1994.

[12] Represented as lettuce.

[13] Drysdale, Alan; Grysikiewicz, Mike; Musgrove, Velda. Life Sciences Project Annual Report, 1996, Table 5.1-2.

Table 4. Quantities of Edible and Inedible Biomass Grown.

Crop	Dry Edible Biomass Growth Rate (kg/m^2d)[14]	Dry Inedible Biomass Growth Rate (kg/m^2d)[14]	Wet Edible Biomass Grown (kg/d)	Wet Inedible Biomass Grown (kg/d)	Dry Edible Biomass Grown (kg/d)	Dry Inedible Biomass Grown (kg/d)
Wheat	**0.0177**	**0.090**	**0.427**	**20.87**	**0.369**	**1.878**
Soybean	**0.0057**	**0.012**	**0.708**	**3.644**	**0.242**	**0.510**
Potato	**0.035**	**0.015**	**1.103**	**0.619**	**0.217**	**0.093**
Sweet Potato	**0.012**	**0.005**	**0.249**	**0.186**	**0.074**	**0.028**
Tomato	**0.0098**[15]	**0.018**	**0.690**	**1.206**	**0.033**	**0.060**
Mix	**0.0058**[16]	**0.0004**	**0.485**	**0.025**	**0.019**	**0.001**
Total			**3.661**	**26.55**	**0.955**	**2.571**
Total per Person per Day			0.915	6.637	0.239	0.643

Table 5. Possible Transpiration Rates and Resultant Loading to the WRS.

Crop	Area (m^2)	Transpiration Rate $(kg/m^2\text{-}d)$[13]	Loading to WRS (kg/d)
Wheat	**20.87**	**5.55**	**115.8**
Soybean	**42.51**	**4.32**	**183.6**
Potato	**6.19**	**4.74**	**29.3**
Sweet Potato	**6.19**	**4.74**	**29.3**
Tomato	**3.35**	**1.58**	**5.3**
Mix	**3.35**	**1.58**	**5.3**
Total			368.7

If one assumes that 11,820 kJ of energy from food are required per crewmember per day[17], then only 29% of the crew energy requirement is satisfied from BPC1 (see Table 7). A quantity of packaged food must be supplied to the crew, based on energy and nutritional requirements. The composition of the packaged food will affect the products of human metabolism.

[14] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSA-ADV-371, JSC 39317, June 18, 1999. Table 3.11.1.

[15] Drysdale, Alan; Beavers, Dan; Posada, Velda. KSC Life Sciences Project Annual Report, 1997, Table 3.1.

[16] Edible growth rate for lettuce.

[17] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, section 4.1.4.1.

If it is assumed that any packaged food that must be supplied to the crew is 40% water[18] and 5% fiber by mass, and that dry food energy percentages for protein, carbohydrate, and fat are 15%, 50% and 35%, respectively[19], then each crew member requires 0.73 kg of packaged food per day (see Table 8 and Table 9). Each crewmember would then consume 0.73 kg of packaged food and 0.84 kg of wet, edible crop per day, for a total of 1.57 kg of food per day. Table 9 breaks down the composition of all consumed food from the assumed scenario of crop production and food resupply. The number of moles of protein, carbohydrate and fat given in the rightmost column of Table 9 is of interest for human metabolism stoichiometry (see section 4.3).

[18] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSA-ADV-371, JSC 39317, June 18, 1999. Footnote 32.

[19] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, Figure 7, Diet ‘A’.

Table 6. Processing Efficiencies and Quantities of Crops Available for Consumption.

Crop	Processing Efficiency[20] (%)	Wet Edible Crop Grown (kg/d)	Wet Edible Crop Wasted (kg/d)	Wet Edible Crop Eaten (kg/d)
Wheat	**90**	**0.427**	**0.043**	**0.384**
Soybean	**80**	**0.708**	**0.142**	**0.567**
Potato	**95**	**1.103**	**0.055**	**1.047**
Sweet Potato	**95[21]**	**0.249**	**0.012**	**0.236**
Tomato	**95[22]**	**0.690**	**0.034**	**0.655**
Mix	**95[23]**	**0.485**	**0.024**	**0.460**
Total		**3.661**	**0.311**	**3.350**
Total per Person[24]		0.915	0.078	0.838

Table 7. Energy Content of Edible Biomass Grown in Test Time Frame[25].

Crop	Energy from Protein (kJ/d)	Energy from Carbohydrate (kJ/d)	Energy from Fat (kJ/d)	Total Energy from Edible Crop (kJ/d)
Wheat	**853**	**4434**	**327**	**5615**
Soybean	**1498**	**1278**	**1769**	**4545**
Potato	**389**	**2821**	**46**	**3256**
Sweet Potato	**69**	**1017**	**57**	**1142**
Tomato	**111**	**304**	**55**	**469**
Mix	**104**	**187**	**40**	**332**
Total Grown	**3024**	**10041**	**2294**	**15,359**
Total Eaten	**2699**	**8963**	**2048**	**13,710**
Total Eaten per Person	675	2241	512	3427

Table 8. Composition of Packaged Food, Excluding Minerals.

[20] Drysdale, Alan; Grysikiewicz, Mike; Musgrove, Velda. Life Sciences Project Annual Report, 1996, Table 5.1-2.

[21] Assumed to be the same as potato.

[22] Assumed to be the same as the mix (lettuce).

[23] Represented in Drysdale 1996 as lettuce.

[24] Not considering food processing wastes/plate wastes.

[25] Assuming 4-kCal/g protein (16.74 kJ/g protein), 4-kCal/g carbohydrate (16.74 kJ/g carbohydrate), and 9 kCal/g fat (37.66 kJ/g fat).

Compound	**Energy Content (%)**	**Mass (%)**	**Energy Content per Mass of Packaged Food (kJ/kg)**
Protein	15	10	1714
Carbohydrate	50	34	5713
Fat	30	11	3999
Water	0	40	0
Fiber	0	5	0
Total (kJ/kg)			11426
Required Energy from Packaged Food (kJ/per-d)			11820 - 3427 = 8393
Required Mass of Packaged Food per Person per Day[26] (kg/per-d)			8393 kJ/per-d ÷ 11426 kJ/kg = 0.73kg/per-d

Table 9. Composition of Food Eaten, Excluding Minerals.

Compound	Mass Eaten from Crops (kg/d)	Mass Eaten from Resupply (kg/d)	Total Mass Eaten (kg/d)	Total Moles Eaten (mol/d)
Protein	**0.160**	**0.302**	**0.462**	**5.565**
Carbohydrate	**0.531**	**1.006**	**1.538**	**8.542**
Fat	**0.054**	**0.313**	**0.367**	**1.433**
Water	**2.397**	**1.179**	**3.575**	**198.6**
Fiber	**0.103**	**0.147**	**0.251**	**1.548**
Total	**3.245**	**2.947**	**6.193**	**215.7**
Total per Person	0.838	0.737	1.548	53.93

Given the production rates and compositions of the crops in BPC1, one can calculate the CO_2, H_2O, and HNO_3 usage rate as well as the O_2 production rate for BPC1. Stoichiometry for crop production of protein, carbohydrate, fat, fiber and lignin is taken from Volk and Rummel, 1987. Table 10 shows the compositions of reactants CO_2, H_2O, and HNO_3 and products edible protein, carbohydrate, fat, and O_2 from Volk and Rummel's paper.

Table 11 lists reactants and products in terms of moles and mass for crop growth in BPC1 for the overall reaction of edible and inedible biomass growth.

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[26] This is the mass of food that must be consumed. To calculate the total mass of food that must be resupplied, divide by the packaged food processing efficiency (assumed to be 93% for this study).

Table 10. Chemical Compositions of Reactants and Products of Plant Growth.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Carbon Dioxide	CO_2	**83**
Water	H_2O	**180**
Nitric Acid	HNO_3	**63**
Protein (edible or inedible)	C_4H_5ON	**32**
Carbohydrate	$C_6H_{12}O_6$	**90**
Fat	$C_{16}H_{32}O_2$	**851**
Fiber	$C_6H_{10}O_5$	**420**
Lignin	$C_{10}H_{11}O_2$	**44**
Oxygen	O_2	**18**

Table 11. Reactants and Products in Crop Growth with Production of Crops in BPC1.

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Carbon Dioxide	**151.4**	**6.663**
Water	**106.1**	**1.910**
Nitric Acid	**13.02**	**0.820**
Protein (edible)	**2.175**	**0.181**
Carbohydrate	**3.330**	**0.599**
Fat	**0.238**	**0.061**
Protein (inedible)	**10.84**	**0.900**
Fiber	**8.654**	**1.402**
Lignin	**2.366**	**0.386**
Oxygen	**183.3**	**5.864**

The overall reaction of crop growth for growth of 45% of the required food mass in the BIO-Plex is:

$$151.4\ CO_2 + 106.1\ H_2O + 13.02\ HNO_3 \rightarrow 13.02\ C_4H_5ON + 3.330\ C_6H_{12}O_6 + 0.238\ C_{16}H_{32}O_2 + 8.654\ C_6H_{10}O_5 + 2.366\ C_{10}H_{11}O_2 + 183.3\ O_2$$

It is assumed that edible soybean and wheat must be dried to a moisture content of 14% for storage purposes,[27] then 77% of the water in wheat will be lost upon drying, and 79% of the water in soybean will be lost upon drying. Thus, if 100% of the grown edible wheat and soybean is dried,[27] then a total of 0.411 kg/d of water must be released to the air passing over the crops in the crop dryer. Assuming a constant wet bulb temperature and that mass transfer equilibrium is reached instantaneously, if the inflow temperature of

[27] Laurie Peterson, personal communication dated August 1999.

air to the crop dryer is 303 K (86 ºF; 30 ºC)[28], the humidity ratio of crew air is 0.01, and it's desired to have an outflow air temperature of 295 K, then 102.8 kg of air from the crew loop is required to pass though the crop dryer per day for steady-state conditions. Such an airflow at steady-state conditions would result in an outflow humidity ratio of 0.014. A crop dryer sized to pass only 102.8 kg of air per day is unconventionally small[29]. However, such a crop dryer is assumed here, for the purposes of considering truly steady-state conditions. Future investigations of system flowrates will include dynamical systems that account for time required to reach mass transfer equilibrium. It is assumed that water from dried crops is eventually condensed and treated in the WRS.

4.2 Food Processing and Preparation System

The production rate of edible material by BPC1 is required to determine food processing heating and cooling requirements in the BIO-Plex. The primary food-processing unit of interest for the Pinch Technique that requires heating of inflow streams is the dishwasher. Unvaporized dishwasher water is sent directly to the WRS, and vaporized dishwasher water is assumed be condensed in the HVAC and also sent to the WRS for treatment.

An estimate for the daily water requirements for dish washing is 21.76 kg/d[30]. It is assumed that 99.45% of the spent water (21.64 kg/d) is sent to the WRS directly and that 0.55% (0.12 kg/d) of the spent water is released as water vapor, collected, condensed and sent to the WRS from the HVAC system.

It is assumed that edible crop that is wasted during food processing is sent to the SPS, where crop water is vaporized and transferred to the atmosphere to be eventually condensed and sent to the WRS. Food processing efficiencies are listed in Table 6. Loading to the WRS from wasted edible biomass amounts to 0.208 kg/d. Food preparation water loading to the WRS is estimated at 2.8 kg/d[31].

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[28] Temperature of air for drying wheat should not be higher than 343 K, but the temperature of air for drying soybean should not be higher then 303 K. Thus a temperature of 303 K is assumed for all drying.

[29] Gregg Weaver's BIO-Plex power requirements list gives 130 W for the crop dryer. Based on web site http://www.peerlessmfg.cc/products/dryer1.html, which gives 5 hp for airflow rate of 11,300 cfm, an estimate for the BIO-Plex crop dryer is scaled at 397 cfm (11.24 m^3/min).

[30] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 5.44 kg/per-d.

[31] Pickering, Karen D; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results, 28th International Conference on Environmental Systems, SAE # 981707, 1998, Table 1.

4.3 Human Metabolism and Hygiene

Information on the steady-state flows of reactants and products of human metabolism is required in order to determine loading to the ARS, WRS and SPS. The quantity and composition of food consumed by the crew affects the quantity and composition of the waste products of human metabolism. Oxygen requirements for the crew impact oxygen generation rates in the ARS. Carbon dioxide production by the crew contributes to the quantity of CO_2 that must be removed in the ARS. Wastewater from human metabolism contributes to loading to the WRS, and waste quantity and composition affects loading and stoichiometry in the SPS.

Stoichiometry for human metabolism of protein, carbohydrate and fat is taken from Volk and Rummel, 1987. Table 12 shows the compositions of reactants protein, carbohydrate, fat, and oxygen and products urine solids, feces solids, sweat solids, carbon dioxide and water from Volk and Rummel's paper.

Table 12. Chemical Compositions of Reactants and Products of Human Metabolism.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Protein	C_4H_5ON	**83**
Carbohydrate	$C_6H_{12}O_6$	**180**
Fat	$C_{16}H_{32}O_2$	**256**
Oxygen	O_2	**32**
Urine Solids	$C_2H_6O_2N_2$	**90**
Feces Solids	$C_{42}H_{69}O_{13}N_5$	**851**
Sweat Solids	$C_{13}H_{28}O_{13}N_2$	**420**
Carbon Dioxide	CO_2	**44**
Water	H_2O	**18**

Given the consumption rate of protein, carbohydrate and fat and the assumption that human waste is 79.7% urine solids, 17.4% feces solids and 2.9% sweat solids (mole percents)[32], O_2 consumption as well as CO_2 and H_2O production rates can be calculated.

Table 13 lists reactants and products in terms of moles and mass for human metabolism based upon the diet discussed in section 4.1 of this document for a crew of four persons. It is assumed that the crew does not metabolize ingested fiber, and that its chemical composition is not changed before passing to the solids processing system.

[32] Finn, Cory K. Steady-State System Mass Balance for the BIO-Plex. 28th International Conference on Environmental Systems, SAE #981747, 1998. (From the ALS Requirements Document Table 13).

Table 13. Reactants and Products in Human Metabolism with Production of Crops by BPC1.

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Protein	**5.565**	**0.462**
Carbohydrate	**8.542**	**1.538**
Fat	**1.433**	**0.367**
Oxygen	**85.14**	**2.724**
Urine Solids	**1.759**	**0.158**
Feces Solids	**0.384**	**0.577**
Sweat Solids	**0.064**	**0.027**
Carbon Dioxide	**75.97**	**3.343**
Water	**68.68**	**1.236**

The overall reaction of human metabolism of food with growth of 45% of the required food mass is:

$$5.565\ C_4H_5ON + 8.542\ C_6H_{12}O_6 + 1.433\ C_{16}H_{32}O_2 + 85.14\ O_2 \rightarrow 1.759\ C_2H_6O_2N_2 + 0.384\ C_{42}H_{69}O_{13}N_5 + 0.064\ C_{13}H_{28}O_{13}N_2 + 75.97\ CO_2 + 68.68\ H_2O$$

The amount of water generated metabolically by the crew, plus the amount of water ingested by the crew in the form of food water, drink water and food preparation water is equal to the quantity of water excreted by the crew in the form of water in urine, water in feces, water vapor produced while sweating and water vapor in respired air. If it is assumed that each crew member requires 3.52 kg of drinking and food-ingested water per day[33] then the total outflow of water from the crew will be (3.524 kg/per-d X 4 persons) + 1.236 kg/d = 15.33 kg/d. It is assumed that 58.9% of this total (9.031 kg) is excreted as water vapor from sweat and respired air, 2.3% (0.353 kg) is excreted as water in feces, and 38.8% (5.949 kg) is excreted as water in urine[33]. It is assumed that all excreted water vapor from sweat and respired air is condensed in the HVAC and sent to the WRS. Loadings to the WRS from a four-person crew are assumed to be the same every day as listed in Table 14.

[33] Lange, K.E.; Lin, C.H. Advanced Life Support Program Requirements Definition and Design Considerations, CTSD-ADV-245 (Rev A), JSC 38571, January 1998, Table 13, Nominal Physiological Loads.

Table 14. Loading to the WRS from the Crew.

Source	Loading (kg/d)
Oral Hygiene	**1.44**[34]
Flush Water	**1.96**[35]
Water from Sweat and Respired Air	**9.03**
Water in Urine	**5.95**
Water in Feces	**0.35**
Hand/Face Wash Water	**16.32**[36]
Shower Water	**25.6**[37]
Clothes Wash Water	**49.88**[38]
Total	110.53

It is assumed that 99.45% of shower water, hand/face wash water and clothes wash water (91.29 kg/d) are sent to the WRS directly, and that 0.55% (0.505 kg/d) is evaporated and eventually condensed and sent to the WRS. For the purposes of water supply to the crew and the FPS, it is assumed that only one hot water user may access heated potable water at a time (i.e. the dishwasher will not be run while a crew member is taking a shower, etc). Thus, all crew and FPS water streams that require heating (shower water, face/hand wash water, clothes wash water, and dish washing water) are lumped into one overall steady-state flowrate of 113.56 kg/d.

It is assumed that one average sized load of laundry is done per day and that 228 m^3/d (294.1 kg/d) of air is allotted for clothes drying[39].

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[34] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 0.36 kg/per-d.

[35] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 0.49 kg/per-d.

[36] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 4.08 kg/per-d.

[37] Pickering, Karen D.; Edeen, Marybeth A. Lunar-Mars Life Support Test Project Phase III Water Recovery System Operation and Results. 28th International Conference on Environmental Systems, SAE #981707, 1998.

[38] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 15, 12.47 kg/per-d.

[39] This is 200cfm airflow. This is from www.doityourselfparts.com/images/APPLIANCES/LAUNDRY/SPEC_DRYERS.jpg

4.4 Solids Processing System

Steady-state flowrates of reactants and products to and from the SPS are required to determine impacts on the rest of the system. The amount and composition of solid waste sent to the SPS affects the flowrate and composition of the products of solid waste oxidation. Oxygen consumed by the SPS affects the amount of oxygen generation that the ARS must perform. Carbon dioxide produced by the SPS impacts the amount of CO_2 removal that the ARS must do. The amount of nitrogen gas that is produced by the SPS reduces the amount of leakage makeup gas that must be supplied to the system. The amount of water that is produced by the SPS affects the loading to the WRS.

For the 120-day BIO-Plex test, 25% of the solid products of human metabolism, inedible biomass and wasted edible biomass are oxidized in the solids processing system. Table 15 shows the compositions of reactants urine solids, feces solids, sweat solids, protein, carbohydrate, fat, fiber, lignin and oxygen as well as products carbon dioxide, water and nitrogen gas. Chemical compositions of reactants and products are taken from Volk and Rummel, 1987. Total wet solids mass loading to the SPS is 31.42 kg/d. The wet solids are 97% water by mass, thus dry solids used in the stoichiometric calculation below are 0.930 kg/d. It is assumed that water delivered to the SPS outflow air is eventually condensed and sent to the WRS.

Such a small amount of waste is not typically incinerated on a continuous basis. For instance, in the LMLSTP Phase III Test Bed, approximately 3840 mL of 50% fecal/water slurry were collected and burned every 4 days for approximately 3.2 hours at a rate of 20mL/min. However, consideration of steady-state conditions with BPC1-grown crops and 25% of solid waste treatment necessitates the assumption of use of an atypically small incinerator vessel. Startup conditions (specifically startup power requirements) are ignored, and it is assumed that a steady-state temperature is maintained within the incineration vessel, with continuous feed and airflow through the system.

Table 15. Chemical Compositions of Reactants and Products of Solid Waste Oxidation.

Reactant or Product	Chemical Formula	Molecular Weight (g/mol)
Urine Solids	$C_2H_6O_2N_2$	**90**
Feces Solids	$C_{42}H_{69}O_{13}N_5$	**851**
Sweat Solids	$C_{13}H_{28}O_{13}N_2$	**420**
Protein	C_4H_5ON	**83**
Carbohydrate	$C_6H_{12}O_6$	**180**
Fat	$C_{16}H_{32}O_2$	**256**
Fiber	$C_6H_{10}O_5$	**162**
Lignin	$C_{10}H_{11}O_2$	**163**
Oxygen	O_2	**32**
Carbon Dioxide	CO_2	**44**
Water	H_2O	**18**
Nitrogen Gas	N_2	**28**

Table 16 lists reactants and products in terms of moles and mass for solid waste oxidation based upon the diet discussed in section 4.1 of this document, with BPC1- provided crops and treatment of 25% of the solid wastes.

Table 16. Reactants and Products in Solid Waste Oxidation with Production of Crops in BPC1 and Treatment of 25% of Solid Wastes (by mass).

Compound	Quantity Reacted or Produced (mol/d)	Quantity Reacted or Produced (kg/d)
Urine Solids	**0.440**	**0.040**
Feces Solids	**0.170**	**0.144**
Sweat Solids	**0.016**	**0.007**
Protein (edible and inedible)	**2.768**	**0.230**
Carbohydrates	**0.089**	**0.016**
Fat	**0.006**	**0.002**
Fiber	**2.443**	**0.396**
Lignin	**0.591**	**0.096**
Oxygen	**45.70**	**1.462**
Carbon Dioxide	**40.49**	**1.782**
Water	**30.42**	**0.548**
Nitrogen Gas	**2.264**	**0.063**

The overall reaction of solid waste oxidation with BPC1-grown crops and treatment of 25% of the solid wastes is:

$$0.440\ C_2H_6O_2N_2 + 0.170\ C_{42}H_{69}O_{13}N_5 + 0.016\ C_{13}H_{28}O_{13}N_2 + 2.768\ C_4H_5ON + 0.089\ C_6H_{12}O_6 + 0.006\ C_{16}H_{32}O_2 + 2.443\ C_6H_{10}O_5 + 0.591\ C_{10}H_{11}O_2 + 45.70\ O_2 \rightarrow 40.49\ CO_2 + 30.42\ H_2O + 2.264\ N_2$$

If it is assumed that 50% of the O_2 in the inlet air to the SPS is utilized in oxidation, then the required air flowrate through the SPS is 12.73-kg/d air. This flowrate is based upon oxidation stoichiometry and the composition of the air (20.6% O_2 by volume) in the crew air loop (see Table 18 below).

4.5 Atmosphere Revitalization System

Steady-state mass flows of atmospheric gases must be adjusted for leakage that occurs from the BIO-Plex chamber. During the 120-day test, the BIO-Plex configuration will consist of a Biomass Production Chamber, Life Support Chamber, Habitation Chamber, Interconnecting Tunnel, and Airlock, all of cylindrical geometry[40]. A Utilities Distribution Module will be included in the BIO-Plex, but it will be separated atmospherically from the rest of the chambers[41]. Table 17 shows the volume of the BIO-Plex during the 120-day test, disregarding the Utilities Distribution Module.

Table 17. Volumes of the BIO-Plex in the 120-day Test, Excluding the Utilities Distribution Module[42].

Component	Diameter (m)	Length (m)	Volume (m^3)
BPC1	**4.60**	**11.30**	**187.79**
Life Support Chamber	**4.60**	**11.30**	**187.79**
Habitation Chamber	**4.60**	**11.30**	**187.79**
Interconnecting Tunnel	**3.70**	**19.20**	**206.44**
Airlock	**3.70**	**4.60**	**49.46**
Total			819.28

As mentioned in section 4, 'Determination of Steady-State Mass Flowrates', separate plant/crew air loops will be incorporated for the 120-day test. Table 18 shows the estimated daily gas leakage rates for the air loop involving the Life Support Chamber, Habitation Chamber, Interconnecting Tunnel and Airlock, assuming an Earth-normal atmospheric composition, temperature of 20 ºC, humidity ratio of 0.01, and a leakage rate of 1% by volume per day. Table 19 shows the estimated daily gas leakage rates for the air loop for BPC1 assuming a BPC-specific atmospheric composition, temperature of 25 ºC,

[40] Tri, Terry O. Bioregenerative Planetary Life Support Systems Test Complex (BIO-Plex): Test Mission Objectives and Facility Development. 29th International Conference on Environmental Systems, SAE #1999-01-2186, 1999.

[41] Tri, Terry. Personal communication dated 7/22/99.

[42] Kirby, Gina M. Bioregenerative Planetary Life Support Systems Test Complex: Facility Description and Testing Objectives. 27th International Conference on Environmental Systems, SAE #972342, 1999.

humidity ratio of 0.012, and a leakage rate of 1% by volume per day. Table 20 shows total leakage rates of gases from the BIO-Plex.

Table 18. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

Gas	Partial Pressure (atm)	Volume in BIO-Plex (m^3)	Leakage (m^3/d)	Leakage (mol/d)	Leakage (kg/d)
Nitrogen	**0.774**	**488.8**	**4.888**	**203.2**	**5.689**
Oxygen	**0.206**	**130.2**	**1.302**	**54.15**	**1.733**
Carbon Dioxide	**0.004**	**2.493**	**0.025**	**1.036**	**0.046**
Water Vapor	**0.016**	**9.971**	**0.100**	**4.145**	**0.075**
Total	1.000	631.5	6.315	262.5	7.542

Table 19. Gas Leakage Rates from BPC1 of the BIO-Plex for the 120-day Test.

Gas	Partial Pressure (atm)	Volume in BIO-Plex (m^3)	Leakage (m^3/d)	Leakage (mol/d)	Leakage (kg/d)
Nitrogen	**0.778**	**145.4**	**1.454**	**60.43**	**1.692**
Oxygen	**0.203**	**38.73**	**0.387**	**16.10**	**0.515**
Carbon Dioxide	**0.0012**[43]	**0.222**	**0.002**	**0.092**	**0.004**
Water Vapor	**0.019**	**3.493**	**0.034**	**1.452**	**0.026**
Total	1.000	187.8	1.878	78.08	2.237

Table 20. Total Leakage Rate from the BIO-Plex for the 120-day Test.

Gas	Leakage Rate (kg/d)
Nitrogen	**7.382**
Oxygen	**2.248**
Carbon Dioxide	**0.050**
Water Vapor	**0.101**
Total	9.780

The flows of gases to/from the atmosphere are based on stoichiometric calculations for flows to/from the Crew, BPC1 and SPS. Appropriate partial pressures and atmospheric compositions must be maintained through atmosphere revitalization and addition of makeup gases. Physical/chemical atmosphere revitalization techniques considered for this

[43] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999. Table 3.2.1.

study that may require heating or cooling of mass flows include CO_2 removal, O_2 generation and trace contaminant control.

The required rate of CO_2 removal for the crew air loop for steady-state conditions can be calculated by accounting for CO_2 output by humans, CO_2 output by the SPS, and the loss of CO_2 from the atmosphere through leakage. The required rate of O_2 removal for the BPC1 air loop for steady-state conditions can be calculated by accounting for O_2 production by the crops and the loss of O_2 from the atmosphere through leakage.

Table 21 shows the removal and makeup requirements of CO_2 and O_2 for the crew and BPC1 air loops. Positive values indicate a removal requirement for a particular gas, and negative values indicate a makeup requirement for a particular gas. In order to maintain the desired air composition of the crew and BPC1 air loops as defined in Table 18 and Table 19, the air flowrate from the crew air loop to the CO_2 removal unit should be 840 kg/d (5.079 kg/d CO_2). Net O_2 deficits in the system (5.919 kg/d) will require electrolysis of water at a rate of 0.642 kg/d, which is supplied from WRS potable water to supply 0.571 kg/d O_2. Electrolysis of 0.642 kg/d of water produces 0.071 kg/d of H_2, which is vented. The remainder of the oxygen deficit in the crew air loop will be compensated for by excess oxygen from the BPC1 air loop.

In order to maintain the desired air composition of the crew and BPC1 air loops as defined in Table 18 and Table 19, the air flowrate from the BPC1 air loop to the O_2 removal unit should be 23.23 kg/d (5.349 kg/d O_2). Net CO_2 deficits in the BPC1 chamber will require supply of CO_2 from the CO_2 removal unit at a rate of 5.079 kg/d and from CO_2 storage at a rate of 1.588 kg/d. Table 22 summarizes mass flows in the ARS.

Table 21. Removal and Makeup Requirements of Gases in the Example System.

Gas	Crew Removal/Makeup Requirements[44, 45] (kg/d)	BPC1 Removal/Makeup Requirements[46] (kg/d)
CO_2	**+5.079**	**-6.667**
O_2	**-5.919**	**+5.349**

Airflow rates to the trace contaminant control system (TCCS) are assumed to be identical to those in the LMLSTP Phase III 90-day Test Bed at 1579 kg/d (850 L/min).

Table 22. Summary of Mass Flows in the ARS at Steady State.

Compound	Flowrate (kg/d)	Origin	Destination
CO_2	**5.079**	**Crew Atmosphere**	**CO_2 Scrubber**
O_2	**5.349**	**BPC1 Atmosphere**	**O_2 Scrubber**
H_2O	**0.642**	**WRS**	**O_2 Generation Unit**
CO_2	**5.079**	**CO_2 Scrubber**	**BPC1 Atmosphere**
CO_2	**1.588**	**CO_2 Storage**	**BPC1 Atmosphere**
O_2	**5.920**	**O_2 Scrubber**	**Crew Atmosphere**
O_2	**0.571**	**O_2 Generation Unit**	**Crew Atmosphere**
H_2	**0.071**	**O_2 Generation Unit**	**Vent**

4.6 Water Recovery System

Water flows to the WRS have been discussed previously and include those listed in Table 23.

[44] See Table 13. Reactants and Products in Human Metabolism with Production and Table 18. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

[45] See Table 16. Reactants and Products in Solid Waste Oxidation with Production of Crops in BPC1 and Treatment of 25% of Solid Wastes (by mass). and Table 18. Gas Leakage Rates from the Habitation Chamber, Life Support Chamber, Interconnecting Tunnel and Airlock of the BIO-Plex for the 120-day Test.

[46] See Table 11. Reactants and Products in Crop Growth with Production of and Table 19. Gas Leakage Rates from BPC1 of the BIO-Plex for the 120-day Test.

Table 23. Daily greywater flows to the WRS for the Example System.

Subsystem	Source	Steady-State Flowrate (kg/d)
BPC1	**Inedible Biomass Water**[47]	**23.98**
	Crop Transpirate	**368.7**
FPS[48]	**Dried Crop Water**	**0.411**
	Dish Washing Water	**21.76**
	Wasted Edible Crop Water	**0.208**
	Food Preparation Water	**2.800**
	Water Lost in Cooking	**1.226**
	Washing/Sanitizing	**175.0**
Crew	**Oral Hygiene Water**	**1.440**
	Flush Water	**1.960**
	Sweat and Respired Water	**9.108**
	Urine Water	**6.004**
	Feces Water	**0.364**
	Hand/Face Washing Water	**16.32**
	Shower Water	**25.60**
	Clothes Washing Water	**49.90**
SPS	**SPS Product Water**[49]	**0.548**
Total		705.4

Airflow rates through the air evaporation system in the LMLSTP Phase III test were approximately 40 cfm (2104 kg/d) for treating a greywater flowrate of 16.2 kg/d (15% of the greywater loading). Thus, it will be assumed that a similar arrangement in the BIO-Plex that treats 105.8 kg/d (15% of greywater loading) would have an air flowrate of 13,742 kg/d.

4.7 Summary of Flowrates

Table 24 summarizes the steady-state flowrates that require heating or cooling in the example system. Mass flows consist of either water or air, and they have been categorized so in Table 24.

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[47] See section 4.1

[48] See section 0.

[49] See Table 16. Reactants and Products in Solid Waste Oxidation with Production of Crops in BPC1 and Treatment of 25% of Solid Wastes (by mass).

Table 24. Steady-State Mass Flowrates of Interest for the Pinch Technique in the Example System.

Stream	Location	Steady-State Flowrate
Water	**Crew/FPS (hygiene water)**	**113.6 kg/d**
	WRS (greywater)	**705.37 kg/d**
Air	**Clothes dryer**	**294.1 kg/d**
	Crop dryer	**102.8 kg/d**
	SPS	**12.73 kg/d**
	CO_2 removal unit	**840.1 kg/d**
	TCCS	**1579 kg/d**
	AES	**13,742 kg/d**

5 Determining Flow Characteristics for Application of the Pinch Technique

In order to apply the Pinch Technique, mass flows that require heating or cooling must be assessed for their heat duty, considering the mass flowrate, supply and target temperatures, and heat of vaporization and/or reaction.

In order to have maximal flexibility in application of the Pinch Technique to hot and cold streams in the example system, typically applied heat exchangers within a unit are disregarded. Excluding unit-contained heat exchangers from the example design allows for trading of waste heat from any hot stream to any cold stream within the BIO-Plex.

Water flows that require heating or cooling in the example system are hygiene/clothes washer/dishwasher water (collectively referred to as hygiene water) and greywater to the APCOS. The supply and target temperatures for these water flows are fixed and will not be considered for alteration in reusing waste heat.

Air flows that require heating or cooling in the example system are air to the 4BMS, fluidized combustion unit air, catalytic gas cleanup air, TCCS air (Englehard catalyst#1 and #2), crop dryer air, clothes dryer air, and air through the AES. The large waste heat load from BPC1 lamps may be represented with an air-cooling flow stream and a water-cooling flow stream. BPC1 lamp waste heat load is discussed in section 5.10.

In the following sections, each possible hot and cold stream is discussed, along with any degree of flexibility with respective flowrates and temperatures.

5.1 Hygiene Water

All crew and FPS water streams that require heating (shower water, face/hand wash water, clothes wash water, and dish washing water) are lumped into one overall steady-state inflow of 113.56 kg/d as discussed in section 4.3. A target temperature of 341 K (154 ºF; 68 ºC) is assumed for all hygiene water loads. Outflow greywater must be cooled to ambient temperature. Since 0.55% of the heated water is assumed to evaporate, the outflow of greywater is 112.92 kg/d. The nominal heat capacity of water between 295 K (ambient temperature) and 341 K is 4.182 kJ/kg-K.

5.2 APCOS Water

The Aqueous Phase Catalytic Oxidation System requires that 705.4 kg/d greywater be heated to 422K (300 ºF; 149 ºC). It is assumed that waste heat from the AES is not used in a regenerative heat exchanger to heat water entering the APCOS (as was done in the

LMLSTP Phase III test bed), so that the APCOS water must be heated from ambient temperature. The nominal heat capacity of water between 295 K (ambient temperature) and 373 K is 4.188 kJ/kg-K. The nominal heat capacity of steam between 373 K and 422 K is 2.005 kJ/kg-K. APCOS outflow water must then be cooled to ambient temperature.

5.3 Four-Bed Molecular Sieve

The Four-Bed Molecular Sieve CO_2 removal system requires that inflow air at room temperature be passed over a desiccant bed and then cooled to 289K (60 °F; 15.6 °C) before passing over the CO_2 sorption bed. The nominal heat capacity of air between 295 K and is 1.003 kJ/kg-K. The steady-state air flowrate to the 4BMS was determined in section 4.5 to be 840.1 kg/d.

5.4 Fluidized Combustion Unit Air

The steady-state air flowrate to the fluidized bed combustion unit was shown in section 4.4 to be 12.73 kg/d. The target temperature for the inflow air will be assumed to be 1033 K (1400 ºF; 760 ºC), which is the same as that for the LMLSTP Phase III test bed for treating a 50% feces solids slurry. Inflow air must be heated from ambient temperature. The nominal heat capacity of air between 295 K and 1033 K is 1.070 kJ/kg-K. Outflow air from the fluidized bed is sent directly to the catalytic gas cleanup system.

5.5 Catalytic Gas Cleanup Air

Airflow to the catalytic gas cleanup system is identical to that of the fluidized bed combustion unit (12.73 kg/d). Air to the catalytic gas cleanup system is assumed to be heated to 1073 K (1472 ºF; 800 ºC), as was done in the LMLSTP Phase III test bed. The temperature of the air flowing into the catalytic gas cleanup system is 1033 K (1400 ºF; 760 ºC). The nominal heat capacity for air between 1033 K and 1073 K is 1.141 kJ/kg-K.

Outflow air from the catalytic gas cleanup system must be cooled down to ambient temperature from the outflow temperature of 1073 K. The nominal heat capacity of air between 1073 K and 295 K is 1.070 kJ/kg-K.

5.6 TCCS Air

Inflow air to the TCCS was described in section 4.5 as 1579 kg/d. The first unit in the TCCS (ammonia removal catalyst) requires that air be heated to 474 K (394 ºF; 201 ºC) from ambient temperature (295 K), having a nominal heat capacity of 1.009 kJ/kg-K. It is also required that air passing through the second Englehard catalyst (10% of the total airflow) be heated to 674 K (754 ºF; 401 ºC) from 474 K, having a nominal heat capacity of 1.036 kJ/kg-K.

In the LMLSTP Phase III Test Bed, the TCCS incorporated a high efficiency counter flow plate/fin air-to-air heat exchanger that traded waste heat from the outflow stream of the second Englehard catalyst to the inflow air to the headworks of the TCCS. However, a unit-contained heat exchanger will not be included in the assumptions for this study. Thus, the 10% of the total air that exits the second Englehard catalyst must be cooled to 295 K from a temperature of 674 K, at which the nominal heat capacity of air is 1.030 kJ/kg-K. The remaining 90% of the total air exiting the first Englehard catalyst must be cooled to 295 K from 474 K, at which the nominal heat capacity of air is 1.009 kJ/kg-K, before entering the final sorbent bed.

5.7 Crop Dryer Air

The crop dryer air flowrate and air temperatures for the example system were described in section 4.1 (102.8 kg/d inflow at 303 K). The nominal heat capacity of air in this case is 1.004 kJ/kg-K. The heat of vaporization of crop water is assumed to reduce the outflow air to ambient temperature, thus the outflow air does not require cooling.

The incoming air temperature should not exceed 303 K, which is the maximum recommended drying temperature for soybeans. However, a temperature less than 303 K may be used to dry the crops. Saturated air cannot be used for drying purposes; hence the inflow air temperature is limited by the humidity ratio of the crew air loop. However, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air. In future applications of the Pinch Technique supply and target temperatures and air flowrates may be manipulated to maximize utilization of waste heat. However, for this initial investigation, parameters for the crop dryer air are considered as constants.

5.8 Clothes Dryer Air

The clothes dryer air flowrate was mentioned in section 4.3 as 294.1 kg/d. It is assumed that the air inflow temperature for clothes dryer air is 333 K (140 ºF; 60 ºC). If it's assumed that water mass flow equilibrium is instantaneous, the dryer is required to vaporize 0.274 kg of water (0.55% of 49.88 kg; see Table 14), and the inflow humidity ratio is 0.01, then the outflow temperature of the air will be 331.5 K (137 ºF; 58.3 ºC). The nominal heat capacity for air in this case is 1.004 kJ/kg-K.

The incoming air temperature should not exceed 333 K for safety reasons, but the temperature may be reduced. As with the crop dryer air, saturated air cannot be used for drying purposes. The inflow air temperature is limited by the humidity ratio of the crew air loop. Again, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air.

As with the crop dryer air, in future applications of the Pinch Technique, supply and target temperatures and air flowrates may be manipulated to maximize utilization of waste heat. However, for this initial investigation, parameters for the clothes dryer air are considered to be constants.

5.9 Air Evaporation System Air

The WRS has to treat approximately 705.4-kg/d greywater, of which 15% passes through the AES in the example system. It was shown in section 4.6 that air flowrates through the AES will be 13,742 kg/d.

It will be assumed that the AES requires heated air to 338 K (149 ºF; 65 ºC), which was the air inflow temperature in the LMLSTP Phase III test bed air evaporation system. It is assumed that the air must be heated from ambient temperature, yielding a nominal heat capacity of 1.005 kJ/kg-K.

Outflow air must be cooled to ambient temperature (295 K). If an air flowrate of 13,742 kg/d at 338 K (149 ºF; 65 ºC) and a humidity ratio of 0.01 are used to vaporize 105.8 kg/d of water, the outflow temperature of the air will be 319 K (115 ºF; 46.1 ºC).

Similarly to the crop dryer and clothes dryer specifications, AES flowrates and temperatures are flexible. Safety considerations as well as the maximum temperature that AES equipment can withstand determine the upper air temperature limit. An upper temperature limit of 338 K will be assumed, based on consideration for avoidance of skin burns.

As with the crop dryer and clothes dryer, saturated air cannot be used for drying purposes. The inflow air temperature is limited by the humidity ratio of the crew air loop. Again, it is not expected that air with a temperature lower than the ambient temperature will be used for drying, so the crew air ambient temperature may be taken as the lower limit for inlet air. If air from a source other then the crew air loop is used as inlet air, then the lower temperature limit may change, depending on the relative humidity of the inlet air.

Similarly to the crop dryer and clothes dryer, supply and target temperatures and air flowrates may be manipulated to maximize utilization of waste heat in future applications of the Pinch Technique. However, for this initial investigation, parameters for the crop dryer air are considered to be constants.

5.10 Lamp-Cooling Air and Water

It is assumed that center shelf lamps will be water-jacketed. There are four center shelves at 14.17 m2 each, three containing soybean and one containing wheat. Outer and corner shelf lamps are assumed to be air-cooled. There are two outer shelves of 6.19 m2 each, one containing potato and the other containing sweet potato. There are four corner shelves of 3.35 m2 each, two containing wheat, one containing tomato and one containing salad mix crops.

Heat-collecting air through the lamps has limits in terms of flowrate and temperatures that are determined by the maximum temperature which can be experienced by HPS lamps and the minimum air temperature that can flow through the light box without occurrence of condensation on the lamps. Thus, the air and water parameters for lamp cooling are flexible. However, as with all theoretically flexible parameters in this study, constant values will be applied for this initial application of the Pinch Technique. Future investigations will consider variable parameters for flow streams.

Cooling requirements for the light box will depend upon the power load to the BPC1 lamps. In order to determine what percentage of the total available lighting will be used, a plant lighting delivery efficiency must be determined. Plant lighting delivery efficiency is defined as the amount of light delivered for a given amount of energy going into the lighting system. It is assumed here that the BPC1 lighting system is sized based on wheat, since wheat requires the highest photosynthetic photon flux (PPF). Therefore, the wheat tray with the lowest lighting intensity per unit area (2710 W/m^2) is used as the basis for determining the lighting delivery efficiency from which the lighting use percentages for the other trays can be calculated. Using 96 lamps at 400 W each for the 14.17 m^2 wheat crop tray in order to achieve a PPF of 1500 $\mu mols/m^2s$ corresponds to a plant energy delivery efficiency of 0.55 µmols /J. This is consistent with the BVAD, which specifies a range of 1.98 to 5.56 lamps per square meter area to give 1000 $\mu mols/m^2s$[50]. The percentage of available lighting that is actually used in each tray, as shown in Table 25, enables determination of lamp heat loads for each light box of HPS 400 W lamps.

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[50] Drysdale, Alan; Hanford, Anthony. Advanced Life Support Systems Modeling and Analysis Project Baseline Values and Assumptions Document, CTSD-ADV-371, JSC 39317, June 18, 1999, Table 3.10.2.

Table 25. BPC1 Lighting Intensities, Percentage of Available Lighting Used and Resultant Heat Loads.

Crop	PPF Required ($\mu mols/m^2$-s)	Lamps per Tray[51]	Tray Area (m^2)	Light Intensity (W/m^2)[52]	Available Lighting Used (%)	Number of Trays	Photo-period (h)	Steady-State Power Load (kW)
Wheat	1500	96	14.2	2710	100	1	24	38.40
Wheat	1500	30	3.35	3582	75.7	2	24	18.17
Soybean	1000	96	14.2	2710	66.7	3	12	38.42
Potato	1000	60	6.19	3877	46.6	1	12	5.59
Sweet Potato	1000	60	6.19	3877	46.6	1	12	5.59
Tomato	1000	30	3.35	3582	50.4	1	16	4.032
Salad Mix	350	30	3.35	3582	17.7	1	16	1.416
Total								**111.6**

If it is assumed that 66% of the power load must be removed as heat directly from the light boxes[53] (the other 34% must be removed from the growing area), then the required heat load to remove from the light boxes is 73.67 kW.

For water-jacketed lamps[54], it is assumed that the water supply temperature is 323 K (50 °C; 148 °F), the flowrate per lamp is 0.105 gpm (572 kg/d) and the target temperature is 333 K (60 °C; 166 °F). The nominal heat capacity of water between 323 K and 333 K is 4.180 kJ/kg-K. Different supply and target temperatures could be achieved by varying the flowrate through the bulbs, and this may be considered in future applications of the Pinch Technique.

For the large wheat tray in the center shelf, 100% of the available lighting is used, resulting in a power load of 38.40 kW. Thus, for 96 lamps, a cooling water flowrate of 10.08 gpm (54,946 kg/d) is required to remove 25.3kW (66% of the power load) for the specified supply and target temperatures.

For the three soybean shelves with water-jacketed lamps, only 67% of the available lighting is actually used during the illumination period. Thus, only 192 of the 288 lamps are illuminated at any one time, yielding a power load of 76.8 kW. Since the photoperiod

[51] Castillo, Juan. Personal communication, June 1999.

[52] Ballast power of 60 W per lamp is not included.

[53] Ewert, Mike. Unpublished data, personal communication, June 1999.

[54] Gertner, Bruce. Personal communication dated 9/22/99.

is 12 hours per day, the steady-state power load is 38.4 kW. This requires a steady-state water flowrate of 54,946 kg/d (20.16 gpm for 12 hours per day) to remove 25.3 kW (66% of the power load). Thus, the total required steady-state water flowrate for all water-jacketed lamps is 109,892 kg/d for removal of approximately 51 kW of waste heat for the specified supply and target temperatures.

For air-cooled lamps, an air flowrate per lamp of 61cfm (3209 kg/d) at a supply temperature of 339 K (66 °C; 151 °F) and a target temperature of 353 K (80 °C; 176 °F) is assumed for full illumination for 24 hours a day.[53] The nominal heat capacity of air between 339 K and 353 K is 1.005 kJ/kg-K. These parameters enable collection of approximately 0.5 kW of waste heat per lamp, which is accounted for by approximately 400W per lamp, plus fan power and any necessary reheat. This information may be used to determine the required steady-state air flowrates for each of the crop shelves.

For the outer shelves of potato and sweet potato, only 47% of the available lighting is actually used during the illumination period. Thus, only 56 of the possible 120 lamps are illuminated at any one time, yielding a power load of 22.36 kW. If waste heat from fans and reheat is included, then a waste heat load of approximately 28 kW (0.5 kW/lamp x 56 lamps) should be considered. Since the photoperiod for potato and sweet potato is 12 hours per day, the steady-state power load is 14 kW. Since it is desired to remove 66% of this power load with air-cooling, 9.25 kW of waste heat must be removed. This amount of waste heat requires a steady-state air flowrate of 59,404 kg/d for the specified supply and target temperatures.

For the two corner shelves of wheat, each of 3.35 m^2, only 76% of the available lighting is actually used during the 24-hour illumination period. Thus, only 46 of the possible 60 lamps are illuminated at any one time, yielding a power load of 18.17 kW. If waste heat from fans and reheat is included, then a waste heat load of approximately 23 kW (0.5 kW/lamp x 46 lamps) should be considered. Since it is desired to remove 66% of this power load with air-cooling, 15.2 kW of waste heat must be removed. This amount of waste heat requires a steady-state air flowrate of 97,487 kg/d for the specified supply and target temperatures.

For the corner shelf of tomato, having an area of 3.35 m2, only 51% of the available lighting is actually used during the 16-hour illumination period. Thus, only 16 of the possible 30 lamps are illuminated at any one time, yielding a power load of 6.05 kW. If waste heat from fans and reheat is included, then a waste heat load of approximately 8 kW (0.5 kW/lamp x 16 lamps) should be considered. Since the photoperiod for tomato is 16 hours per day, the steady-state power load is 5.33 kW. Since it is desired to remove 66% of this heat load with air-cooling, 3.52 kW of waste heat must be removed. This amount of waste heat requires a steady-state air flowrate of 22,606 kg/d for the specified supply and target temperatures.

For the corner shelf of salad mix, having an area of 3.35 m2, only 18% of the available lighting is actually used during the 16-hour illumination period. Thus, only 6 of the possible 30 lamps are illuminated at any one time, yielding a power load of 2.12 kW. If waste heat from fans and reheat is included, then a waste heat load of approximately 3 kW (0.5 kW/lamp x 6 lamps) should be considered. Since the photoperiod for the salad mix is 16 hours per day, the steady-state power load is 2 kW. Since it is desired to remove 66% of this heat load with air-cooling, 1.33 kW of waste heat must be removed. This amount of waste heat requires a steady-state air flowrate of 8553 kg/d for the specified supply and target temperatures. The sum of all steady-state air flowrates for lamp cooling is thus 188,050 kg/d.

In future applications of the Pinch Technique, the mass flowrate of air may be strategically chosen so as to maximize the usefulness of inlet and outlet air streams in applying the Pinch Technique. If it were assumed that the maximum allowable air temperature in the light boxes is 473 K (392 ºF; 200 ºC), then the minimum inflow temperature is that at which 0.011 (BPC1 air humidity ratio) is the dew point temperature, which is the temperature below which undesirable condensation would occur in the light box. At a humidity ratio of 0.01, the dew point temperature of air is approximately 289 K (60 ºF; 15.6 ºC). If an air stream with a humidity ratio other than that of the BPC1 air were used, then the minimum air inflow temperature would change accordingly.

5.11 Summary

Sections 5.1 through 5.10 describe characteristics of flowrates to consider in application of the Pinch Technique to the example system. Table 26 summarizes the hot and cold streams and their parameters of interest.

Table 26. Cold Streams of Interest in Applying the Pinch Technique to the Example System.

Stream Number	Stream Description	Steady-State Flowrate (kg/d)	Supply Temp. (K)	Target Temp. (K)	Heat Capacity (kJ/kg-K)	Heat Duty (kW)
1	Hygiene Water Inflow	113.6	295	341	4.182	0.253
2a	APCOS Inflow Water	705.4	295	373	4.188	2.667
2b	APCOS Inflow Steam	705.4	373	422	2.005	0.802
3	Fluidized Combustion Unit Inflow Air	12.3	295	1033	1.070	0.112
4	Catalytic Gas Cleanup Inflow Air	12.3	1033	1073	1.141	0.006
5	TCCS Englehard Catalyst #1 Inflow Air	1579	295	474	1.009	3.301
6	TCCS Englehard Catalyst #2 Inflow Air	157.9	474	674	1.036	0.379
7	AES Inflow Air	13,742	295	338	1.005	6.873
8	Crop Dryer Inflow Air	102.8	295	303	1.004	0.010
9	Clothes Dryer Inflow Air	294.1	295	333	1.004	0.130

Table 27. Cold Streams of Interest in Applying the Pinch Technique to the Example System.

Stream Number	Stream Description	Steady-State Flowrate (kg/d)	Supply Temp. (K)	Target Temp. (K)	Heat Capacity (kJ/kg-K)	Heat Duty (kW)
10	Hygiene Water Outflow	112.9	341	295	4.182	-0.251
11a	APCOS Outflow Steam	705.4	422	373	2.005	-0.802
11b	APCOS Outflow Water	705.4	373	295	4.188	-2.667
12	Water-Jacketed Lamps Outflow	109,892	333	323	4.180	-53.165
13	Four-Bed Molecular Sieve Inflow Air	840.1	295	289	1.003	-0.059
14	Catalytic Gas Cleanup Outflow Air	12.3	1073	295	1.070	-0.119
15	TCCS Englehard Catalyst #2 Outflow Air	157.9	674	295	1.030	-0.713
16	TCCS Englehard Catalyst #1 Outflow Air	1421.1	474	295	1.009	-2.971

17	AES Outflow Air	13,742	319	295	1.005	-3.836
18	Clothes Dryer Outflow Air	294.1	331	295	1.004	-0.123
19	Air-cooled Lamp Outflow	188,050	353	339	1.005	-30.634

6 Temperature Interval Analysis and Heat Cascade

6.1 Temperature Intervals

The next step in applying the Pinch Technique is to develop a temperature interval analysis chart for determination of the minimal requirements of external heating and cooling for the system.

For feasible heat exchange between two streams, the hot stream must be hotter than the cold stream at all points. The minimum temperature difference (_T_{min}) between a hot and cold stream that is required in order for heat exchange to occur is a function of the heat exchanger design, but has been assumed to be 10 K for this example system.

Within any temperature interval, the hot and cold streams must always be at least _T_{min} apart. This difference in temperature is assured by constructing a set of temperature intervals such that the interval temperatures for the hot streams are set at _ _T_{min} below the hot stream supply and target temperatures, and the interval temperatures for the cold streams are set at _ _T_{min} above the cold stream supply and target temperatures.

Constant nominal heat capacity values for each stream temperature range are assumed in each interval for this initial application of the Pinch Technique. The heat capacities for water (or steam) and air are given in Table 28 and Table 29 over the range of temperatures that are applicable to flows in the example system. In the case of a phase change, the interval is broken into two intervals (see streams 2 and 11 within intervals 9.1, 9.2, and 9.3). Figure 1 shows the resulting temperature interval analysis graph.

Table 28. Heat Capacities of Water (Gas or Liquid) for a Range of Temperatures.

Cp of Water at atmospheric pressure					
	Temp (°F)	Temp (K)	Temp (°C)	Cp (Btu/lbm-F)	Cp (kJ/kg-K)
gas	300	422.0	148.9	0.475	1.987
	280	410.9	137.8	0.477	1.996
	260	399.8	126.7	0.478	2.000
	240	388.7	115.6	0.481	2.013
	220	377.6	104.4	0.484	2.025
liquid	200	366.5	93.3	1.005	4.205
	180	355.4	82.2	1.003	4.197
	160	344.3	71.1	1.001	4.188
	140	333.2	60.0	0.999	4.180
	120	322.0	48.9	0.999	4.180
	100	310.9	37.8	0.998	4.176
	80	299.8	26.7	0.998	4.176
	60	288.7	15.6	1.000	4.184

Table 29. Heat Capacities of Air for a Range of Temperatures.

Cp of Air at atmospheric pressure					
Temp (K)	Cp (kJ/kg-K)	Temp (K)	Cp (kJ/kg-K)	Temp (K)	Cp (kJ/kg-K)
1080	1.144	800	1.089	520	1.023
1060	1.141	780	1.084	500	1.019
1040	1.137	760	1.080	480	1.015
1020	1.134	740	1.075	460	1.012
1000	1.130	720	1.070	440	1.009
980	1.127	700	1.065	420	1.007
960	1.123	680	1.060	400	1.006
940	1.119	660	1.055	380	1.005
920	1.115	640	1.050	360	1.005
900	1.111	620	1.046	340	1.005
880	1.107	600	1.041	320	1.006
860	1.102	580	1.036	300	1.004
840	1.098	560	1.031	280	1.000
820	1.093	540	1.027		

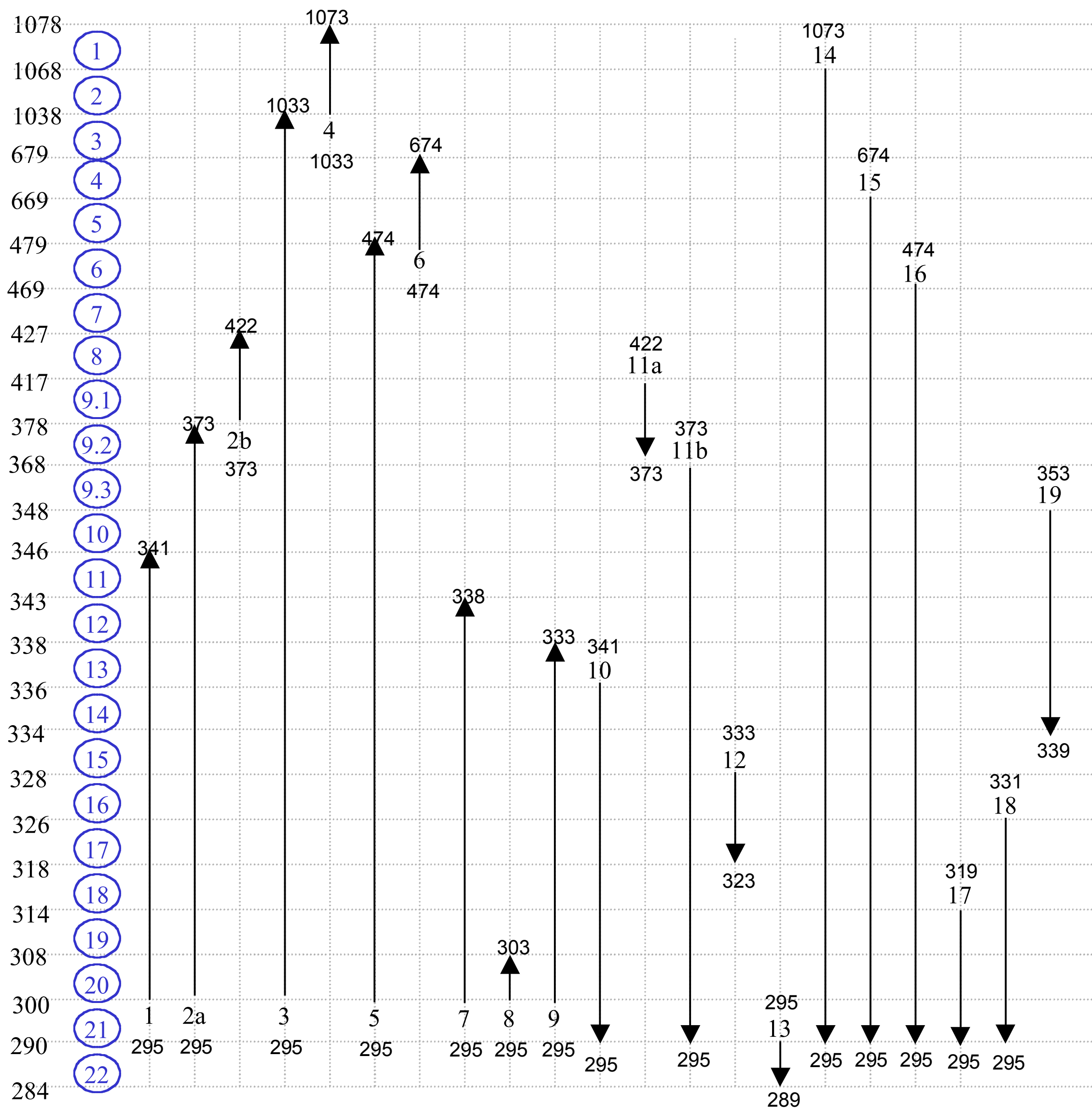


Figure 1. Temperature Interval Analysis for the Example System.

6.2 Heat Cascade

Next, a net enthalpy balance is performed on the system. The temperature difference in each interval, multiplied by the heat capacity flowrate (heat capacity times the material flowrate) gives the enthalpy surplus or deficit within each interval. Table 30 shows the net enthalpy loads within each temperature interval for the example system.

Since any heat available in interval i is hot enough to supply heat to interval i +1, a "heat cascade" can be designed as shown on the left-hand-side of Figure 2. In the heat cascade diagram there are 24 boxes that show the net heat load for each temperature interval. A cumulative heat load for the system appears to the right of the boxes. Starting at the top of the cascade, the cumulative heat load is calculated down the cascade. A negative enthalpy flow is thermodynamically infeasible; therefore, 0.527 kW of external heat must be added to the system. On the right-hand-side of Figure 2, the same heat cascade is performed, with 0.527 kW of external heat added at the top of the cascade. This heat cascades down through the system, giving a feasible, and optimal design where the minimum utility requirements for the system are 0.527 kW of heating and 81.369 kW of cooling. The location of the pinch has been identified as the point where the heat flow is zero, which occurs where the hot streams are at 373K and the cold streams are at 363K.

Table 30. Temperature Interval Analysis for Example System.

Interval Number	$T_i - T_{i+1}$ (K)	CPcold – CPhot (kW/K)	H_i (kW)	Surplus or Deficit
1	10	1.62×10^{-4}	1.62×10^{-3}	Deficit
2	30	1.01×10^{-5}	3.03×10^{-4}	Deficit
3	359	0	0	-
4	10	1.89×10^{-3}	1.89×10^{-2}	Deficit
5	190	1.10×10^{-5}	2.08×10^{-3}	Deficit
6	10	1.66×10^{-2}	1.66×10^{-1}	Deficit
7	42	-3.84×10^{-5}	-1.61×10^{-3}	Surplus
8	10	1.63×10^{-2}	1.63×10^{-1}	Deficit
9.1	39	-3.84×10^{-5}	-1.50×10^{-3}	Surplus
9.2	10	1.78×10^{-2}	1.78×10^{-1}	Deficit
9.3	20	-3.84×10^{-5}	-7.68×10^{-4}	Surplus
10	2	-2.21	-4.41	Surplus
11	3	-2.18	-6.55	Surplus
12	5	-2.02	-10.1	Surplus
13	2	-2.02	-4.04	Surplus
14	2	-2.02	-4.05	Surplus
15	6	1.63×10^{-1}	9.80×10^{-1}	Deficit
16	2	-5.15	-10.3	Surplus
17	8	-5.16	-41.3	Surplus
18	4	1.60×10^{-1}	6.39×10^{-1}	Deficit
19	6	-8.15×10^{-6}	-4.89×10^{-5}	Surplus
20	8	1.19×10^{-3}	9.49×10^{-3}	Deficit
21	10	$-2.22 \times ^{10-1}$	-2.22	Surplus
22	6	$-9.75 \times ^{10-3}$	-5.85×10^{-2}	Surplus

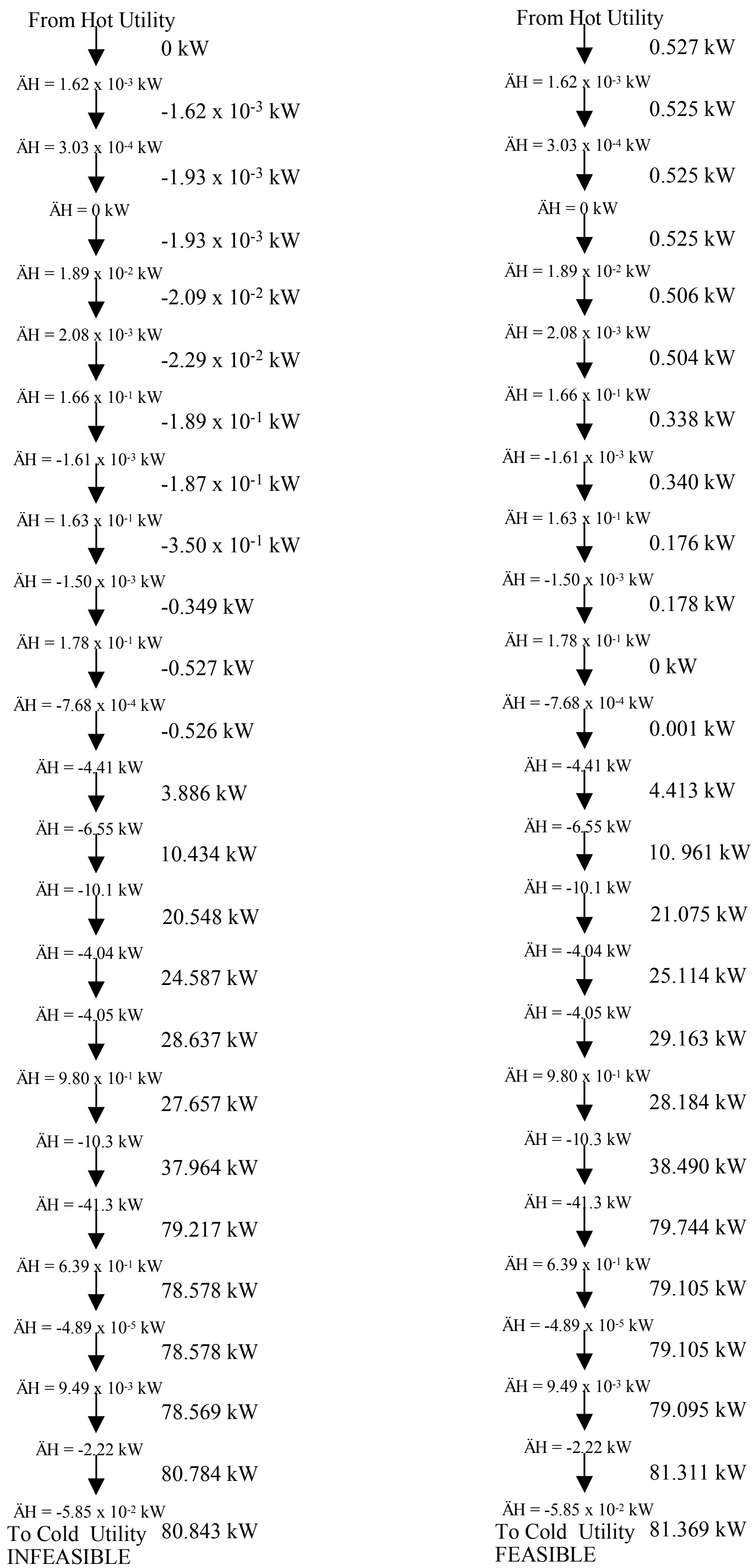


Figure 2. Heat Cascade for the Example System.

7 Heat Exchange Design

Once the energy cascade has been completed, matching hot and cold streams according to the following design principles can develop an optimal system heat exchange design. The three rules of the pinch principle are as follows:

1. Heat must not be transferred across the pinch.
2. There must be no external cooling above the pinch.
3. There must be no external heating below the pinch.

Thus, the design problem should be divided at the pinch, and each part designed separately. For each part, the designer should start at the pinch and move away. Immediately adjacent to the pinch point, the constraints $Cp_{cold} \geq Cp_{hot}$ (immediately above the pinch) and $Cp_{cold} \leq Cp_{hot}$ (immediately below the pinch) must hold for each pair of hot and cold streams that exchange energy. This assures that the temperature difference between hot and cold streams that are exchanging heat remains greater than _T_{min}.

Hot and cold streams should be matched such that heat exchanger loads are maximized, so that the total number of exchangers can be minimized. External heating should only be applied above the pinch temperature (a heat sink), and external cooling should only be applied below the pinch temperature (a heat source).

7.1 Above the Pinch Heat Exchange Network

Table 31 lists the streams, heat capacities and heat duties for all hot and cold streams above the pinch point. Since no utility cooling is to be implemented above the pinch, the design approach is to satisfy each hot stream heat supply with cold streams heat demands while maximizing heat loads in order to minimize the number of heat exchangers required. Another goal is to avoid the exchange of heat between two units that will be physically far apart. Whenever possible, heat should be exchanged between two streams that are in relatively close vicinity to each other to minimize equipment requirements.

In Table 31, the streams are listed in order of heat capacity flowrate, from lowest to highest. Therefore, immediately above the pinch hot streams at the pinch may only be matched with cold streams that are listed above them in Table 31 in order to comply with the rule $Cp_{cold} \geq Cp_{hot}$,.

Table 31. Initial Streams Above the Pinch.

Stream Number	Stream	Hot or Cold	Heat Capacity Flowrate (kW/K)	Heat Duty (kW)
2a	APCOS Inflow	Cold	3.42×10^{-2}	0.342
5	TCCS Englehard Catalyst #1 Inflow	Cold	1.84×10^{-2}	2.047
16	TCCS Englehard Catalyst #1 Outflow	Hot	1.66×10^{-2}	1.676
2b	APCOS Inflow	Cold	1.64×10^{-2}	0.802
11a	APCOS Outflow	Hot	1.64×10^{-2}	0.802
6	TCCS Englehard Catalyst #2 Inflow	Cold	1.89×10^{-3}	0.379
15	TCCS Englehard Catalyst #2 Outflow	Hot	1.88×10^{-3}	0.567
4	Catalytic Gas Cleanup Inflow	Cold	1.62×10^{-4}	0.006
3	Fluidized Combustion Unit Inflow	Cold	1.52×10^{-4}	0.102
14	Catalytic Gas Cleanup Outflow	Hot	1.52×10^{-4}	0.107

Stream #3 (Fluidized Combustion Unit Inflow) may be matched only with stream #14 (Catalytic Gas Cleanup Outflow). Stream #14 is also the only hot stream with a heat capacity flowrate that is less than that of stream #4 (Catalytic Gas Cleanup Inflow). Stream #14 may exchange 0.102 kW of heat with stream #3 in a countercurrent heat exchanger, taking stream #14 from 1043 K to 373 K and taking stream #3 from 363 K to 1033 K. Another countercurrent heat exchanger may then be used to exchange 0.005 kW of heat between stream #14, cooling it from 1073 K to 1043 K, and stream #4, heating it from 1033 K to 1063 K. External heating (0.001 kW) may be used to heat stream #4 from 1063 K to 1073 K. These matches completely satiate the heat supply of stream #14 (0.107 kW).

A similar type of match is seen with the APCOS unit. Stream #11a may exchange 0.342 kW of heat with stream #2a in a countercurrent heat exchanger, taking stream #11a from 394 K to 373 K and taking stream #3 from 363 K to 373 K. Another countercurrent heat exchanger may then be used to exchange 0.460 kW of heat between stream #11a, cooling it from 422 K to 394 K, and stream #2b, heating it from 373 K to 401 K. External heating (0.341 kW) may be used to heat stream #2b from 401 K to 422 K. These matches completely satiate the heat supply of stream #11a (0.802 kW).

From here, it can be seen that stream #5 has to be used to accept both the remainder of the heat load from stream #15 and the heat load from stream #16. Thus, stream #5 must be split. Starting at the pinch, stream #5 may be split such that the heat capacity flowrate of one branch is a compatible match with stream #15 and the other is a compatible match with stream #16. This is done by designing stream #5a to have a heat capacity flowrate equivalent to that of stream #15 and stream #5b to have a heat capacity flowrate equivalent to that of stream #16. Thus, heat may be exchanged between those streams close to the pinch.

In order for stream #5a to have a heat capacity flowrate equal to that of stream #15, 1.88 x 10^{-3} kW/K, it must have a mass flowrate of 161.2 kg/d. Thus, the temperature of stream #5a rises from 363 K to 474 K while exchanging 0.209 kW of heat with stream #15. This takes the temperature of stream #15 to 373 K from 484 K. In order to get the temperature of stream #15 from 674 K to 484 K in the first place, it must exchange 0.358 kW of heat with stream #6. By doing this, the temperature of stream #6 raises from 474 K to 662 K. The temperature of stream #6 may then be raised from 663 K to 474 K with 0.020 kW of external heating. These matches completely satisfy the heat supply of stream #15 (0.567 kW).

If stream #5a has a mass flowrate of 161.2 kg/d, then stream #5b must have a mass flowrate of 1418 kg/d, which results in a heat capacity flowrate of 1.066 x 10^{-2} kW/K. Thus, stream #16 may exchange 1.676 kW of waste heat with stream #5b. This heat exchange lowers the temperature of stream #16 from 474 K to 373 K and raises the temperature of stream #5b from 363 K to 464 K. Stream #5b may then be raised to a temperature of 474 K with 0.165 kW of external heating. Table 32 shows revised stream characteristics for the analysis above the pinch. The previously mentioned matches exhaust the heat supply from the hot streams above the pinch. The heat demands that are not satisfied by the matches are shown in Table 33 and sum to 0.527 kW. This quantity is the minimum amount of utility heating that was determined in the heat cascade of Figure 2.

Table 32. Revised Streams Above the Pinch.

Stream Number	Stream	Hot or Cold	Heat Capacity Flowrate (kW/K)	Heat Duty (kW)
2a	APCOS Inflow	Cold	3.42 x 10^{-2}	0.342
16	TCCS Englehard Catalyst #1 Outflow	Hot	1.66 x 10^{-2}	1.676
2b	APCOS Inflow	Cold	1.64 x 10^{-2}	0.802
11a	APCOS Outflow	Hot	1.64 x 10^{-2}	0.802
5b	TCCS Englehard Catalyst #1 Inflow	Cold	1.07 x 10^{-2}	1.841
6	TCCS Englehard Catalyst #2 Inflow	Cold	1.89 x 10^{-3}	0.379
5a	TCCS Englehard Catalyst #1 Inflow	Cold	1.88 x 10^{-3}	0.209
15	TCCS Englehard Catalyst #2 Outflow	Hot	1.88 x 10^{-3}	0.567
4	Catalytic Gas Cleanup Inflow	Cold	1.62 x 10^{-4}	0.006
3	Fluidized Combustion Unit Inflow	Cold	1.52 x 10^{-4}	0.102
14	Catalytic Gas Cleanup Outflow	Hot	1.52 x 10^{-4}	0.107

Table 33. Unsatisfied Heating Demand Above the Pinch.

Stream Number	Stream	Heat Duty (kW)
4	Catalytic Gas Cleanup Inflow	0.001
2b	APCOS Inflow	0.341
6	TCCS Englehard Catalyst #2 Inflow	0.020
5b	TCCS Englehard Catalyst #1 Inflow	0.165
TOTAL		**0.527**

Figure 3 shows a grid diagram for a heat exchanger network for the example system above the pinch. The hot streams are shown at the top of the figure, running from left to right. Cold streams run across the bottom, from the right to the left. A vertical line joining circles on two matched streams shows a heat exchanger transferring heat between the process streams. Each heat exchanger is assigned a number on the circle denoting the hot stream. Applying the rules of the pinch principle means that there must be no cooler on the section above the pinch (Linnhoff March Online, 1999). External heating is represented as a circle embedded with an ‘H’. Traded heat is listed under the circles on each cold stream, and the temperature progression of each stream is given at the start of a stream and after each heat exchanger.

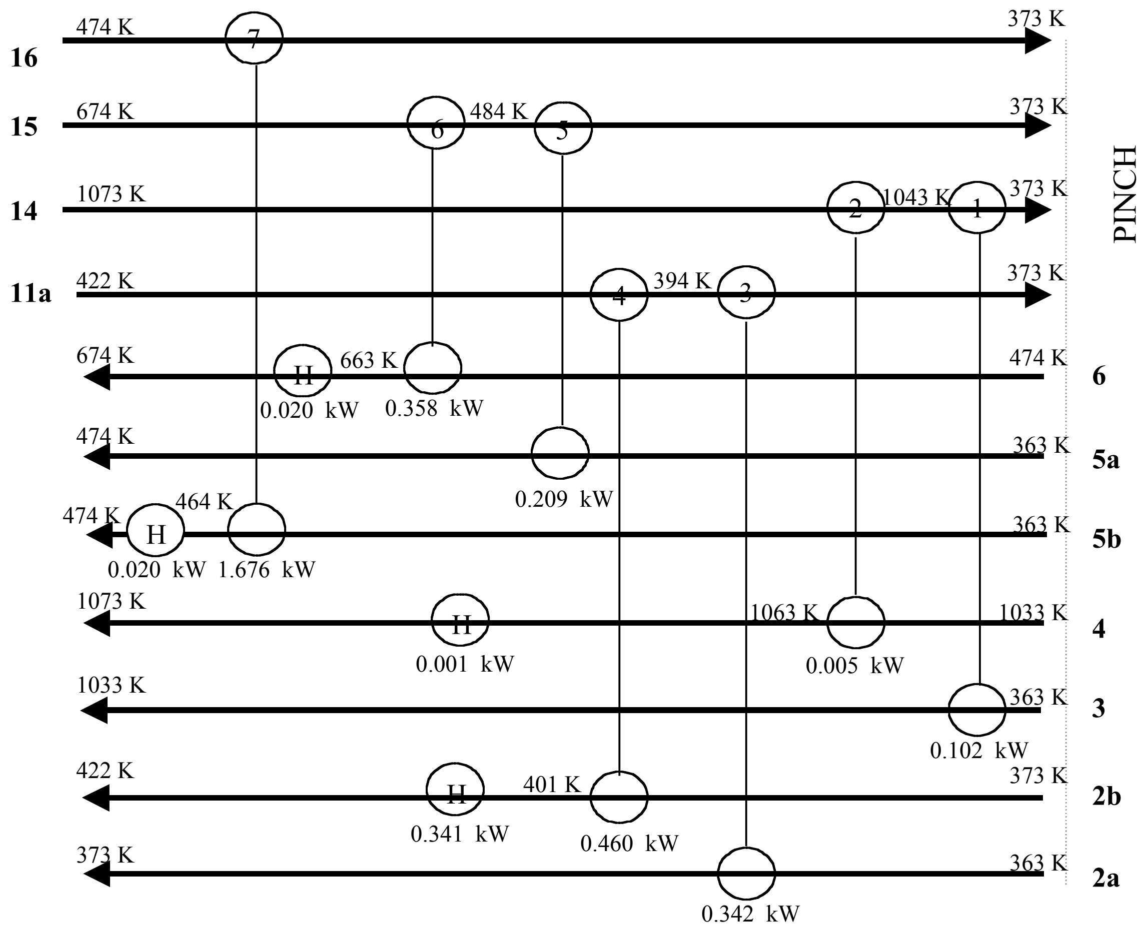


Figure 3. Heat Exchanger Network for Above the Pinch.

7.2 Below the Pinch Heat Exchange Network

Table 34 lists the streams, heat capacities and heat duties for all hot and cold streams below the pinch point. Since no utility heating is to be implemented below the pinch, the design approach is to satisfy each cold stream with hot streams while maximizing heat loads in order to minimize the number of heat exchangers required. As in exchanging waste heat above the pinch, another goal is to avoid the exchange of heat between two units that will be physically far apart. Whenever possible, heat should be exchanged between two streams that are in relatively close vicinity to each other.

In Table 34, the streams are listed in order of heat capacity flowrate, from lowest to highest. Therefore, in order to comply with the rule $Cp_{hot} \geq Cp_{cold}$ immediately below the pinch, cold streams at the pinch may only be matched with hot streams that are listed above them in Table 34.

A first logical approach to the design below the pinch is to use regenerative heat exchangers wherever the hot stream of a unit can completely satisfy the heat demand of the cold stream in that same unit. A logical match is a regenerative heat exchange of 0.104 kW between stream #14 (Catalytic Gas Cleanup Unit outflow) and stream #3 (Fluidized Combustion Unit outflow). This match reduces the temperature of stream #14 from 373 K to 305 K and increases the temperature of stream #3 from 295 K to 363 K. External cooling in the amount of 0.002 kW is then used to reduce the temperature of stream #3 from 305 K to 295 K.

Another logical heat exchange of 2.33 kW between stream #11b (APCOS Outflow) and stream #2a (APCOS Inflow) is noted. This match reduces the temperature of stream #11b from 373 K to 305 K and increases the temperature of stream #2a from 295 K to 363 K. External cooling in the amount of 0.342 kW is then used to reduce the temperature of stream #11b from 305 K to 295 K.

Table 34. Initial Streams Below the Pinch.

Stream Number	Stream	Hot or Cold	Heat Capacity Flowrate (kW/K)	Heat Duty (kW)
12	Water-Jacketed Lamps	Hot	5.317	53.17
19	Air used to cool lamps	Hot	2.188	30.63
17	AES Outflow	Hot	0.160	3.836
7	AES Inflow	Cold	0.160	6.873
11b	APCOS Outflow	Hot	0.034	2.667
2a	APCOS Inflow	Cold	0.034	2.325
5	TCCS Inflow - EH Cat #1	Cold	0.018	1.254
16	TCCS Outflow - EH Cat #1	Hot	0.017	1.294
13	Four Bed Molecular Sieve	Hot	0.010	0.059
1	Hygiene Water	Cold	0.005	0.253
10	Hygiene Water	Hot	0.005	0.251
18	Clothes Dryer Air	Hot	0.003	0.123
9	Clothes Dryer Air	Cold	0.003	0.130
15	TCCS Outflow - EH Cat #2	Hot	0.002	0.147
8	Crop Dryer Inflow	Cold	0.001	0.010
14	Catalytic Gas Cleanup Unit Outflow	Hot	0.0002	0.012
3	Fluidized Combustion Unit Inflow	Cold	0.0002	0.010

Heat exchange between streams #5, #15 and #16 is made possible by splitting stream #5. Stream #5a must have a heat capacity flowrate less than or equal to that of stream #16 in order to exchange heat between them. Thus, if stream #5c has a mass flowrate of 1421 kg/d, then it will have a heat capacity flowrate equal to that of stream #16, and an exchange of 1.129 kW is made by raising stream #5c from 295 K to 363 K and reducing stream #16 from 373 K to 305 K. External cooling in the amount of 0.166 kW is then used to reduce the temperature of stream #16 from 305 K to 295 K.

The remainder of mass flow from stream #5 is denoted as #5d and is 157.6 kg/d, resulting in a heat capacity flowrate that is less than that of stream #15, enabling their exchange of heat near the pinch. Thus, 0.125 kW of waste heat is traded between stream #15, lowering its temperature from 373 K to 305 K, and stream #5d, raising its temperature from 295 K to 363 K. External cooling in the amount of 0.019 kW is then used to reduce the temperature of stream #15 from 305 K to 295 K.

There are no other cases where regenerative heat exchange can completely satisfy a cold stream without violating the $Cp_{hot} \geq Cp_{cold}$ rule. At this point, a reasonable approach must be developed for numerous exchanges of waste heat between units that are spatially far from each other.

Since there is a very large waste heat load associated with stream #19 (Air-Cooled Lamps), a sensible tactic is to break that stream into multiple streams for satisfying all of the remaining cold stream demands, namely, streams #1, #7, #8 and #9. Stream #19 can be split to match or exceed the heat capacity of those cold streams and then used to supply waste heat. Table 35 shows the revised 'Below the Pinch' streams when water from the jacketed lamps is split as necessary to satisfy the remaining cold stream demands. Stream #19a was created to supply stream #7 with 6.873 kW of waste heat, stream #19b was created to supply stream #1 with 0.253 kW of waste heat, and stream #19c was created to supply stream #9 with 0.130 kW of waste heat. Stream #19d is the remaining quantity of air flow from the lamps, and satisfies the 0.0096 kW waste heat demand of stream #8 and still requires 23.37 kW of external cooling.

Table 35. Revised Streams Below the Pinch.

Stream Number	Stream	Hot or Cold	Heat Capacity Flowrate (kW/K)	Heat Duty (kW)
12	Water-Jacketed Lamps	Hot	5.317	53.17
19a	Air used to cool lamps	Hot	0.491	6.873
19b	Air used to cool lamps	Hot	0.018	0.253
19c	Air used to cool lamps	Hot	0.009	0.130
19d	Air used to cool lamps	Hot	1.669	23.38
17	AES Outflow	Hot	0.160	3.836
7	AES Inflow	Cold	0.160	6.873
11b	APCOS Outflow	Hot	0.034	2.667
2a	APCOS Inflow	Cold	0.034	2.325
16	TCCS Outflow - EH Cat #1	Hot	0.017	1.294
5c	TCCS Inflow - EH Cat #1	Cold	0.017	1.129
13	Four Bed Molecular Sieve	Hot	0.010	0.059
1	Hygiene Water	Cold	0.005	0.253
10	Hygiene Water	Hot	0.005	0.251
18	Clothes Dryer Air	Hot	0.003	0.123
9	Clothes Dryer Air	Cold	0.003	0.130
5d	TCCS Inflow – EH Cat #1	Cold	0.002	0.125
15	TCCS Outflow - EH Cat #2	Hot	0.002	0.147
8	Crop Dryer Inflow	Cold	0.001	0.010
14	Catalytic Gas Cleanup Unit Outflow	Hot	0.0002	0.012
3	Fluidized Combustion Unit Inflow	Cold	0.0002	0.010

The previously mentioned matches exhaust the heat demand of the cold streams below the pinch. The heat supplies that are not consumed by the matches that require external cooling are listed in Table 36 and sum to 81.33 kW. This quantity is the minimum amount of utility cooling that was determined in the heat cascade of Figure 2.

Table 36. Unsatisfied Cooling Demand Below the Pinch.

Stream Number	Stream	Heat Duty (kW)
12	Water-Jacketed Lamps Outflow	53.17
19d	Air-Cooled Lamps Outflow	23.17
17	Air Evaporation System Outflow	3.836
11b	APCOS Outflow	0.342
16	TCCS Englehard Catalyst #1 Outflow	0.166
13	Four-Bed Molecular Sieve Inflow	0.059
10	Hygiene Water Outflow	0.251
18	Clothes Dryer Outflow	0.123
15	TCCS Englehard Catalyst #2 Outflow	0.019
14	Catalytic Gas Cleanup Unit Outflow	0.002
TOTAL		**81.33**

Figure 4 shows a grid diagram for a heat exchanger network for the example system below the pinch. The hot streams are shown at the top of the figure, running from left to right. Cold streams run across the bottom, from the right to the left. A vertical line joining circles on two matched streams shows a heat exchanger transferring heat between the process streams. Each heat exchanger is assigned a number on the circle denoting the hot stream. Applying the rules of the pinch principle means that there must be no heater on the section below the pinch (Linnhoff March Online, 1999).

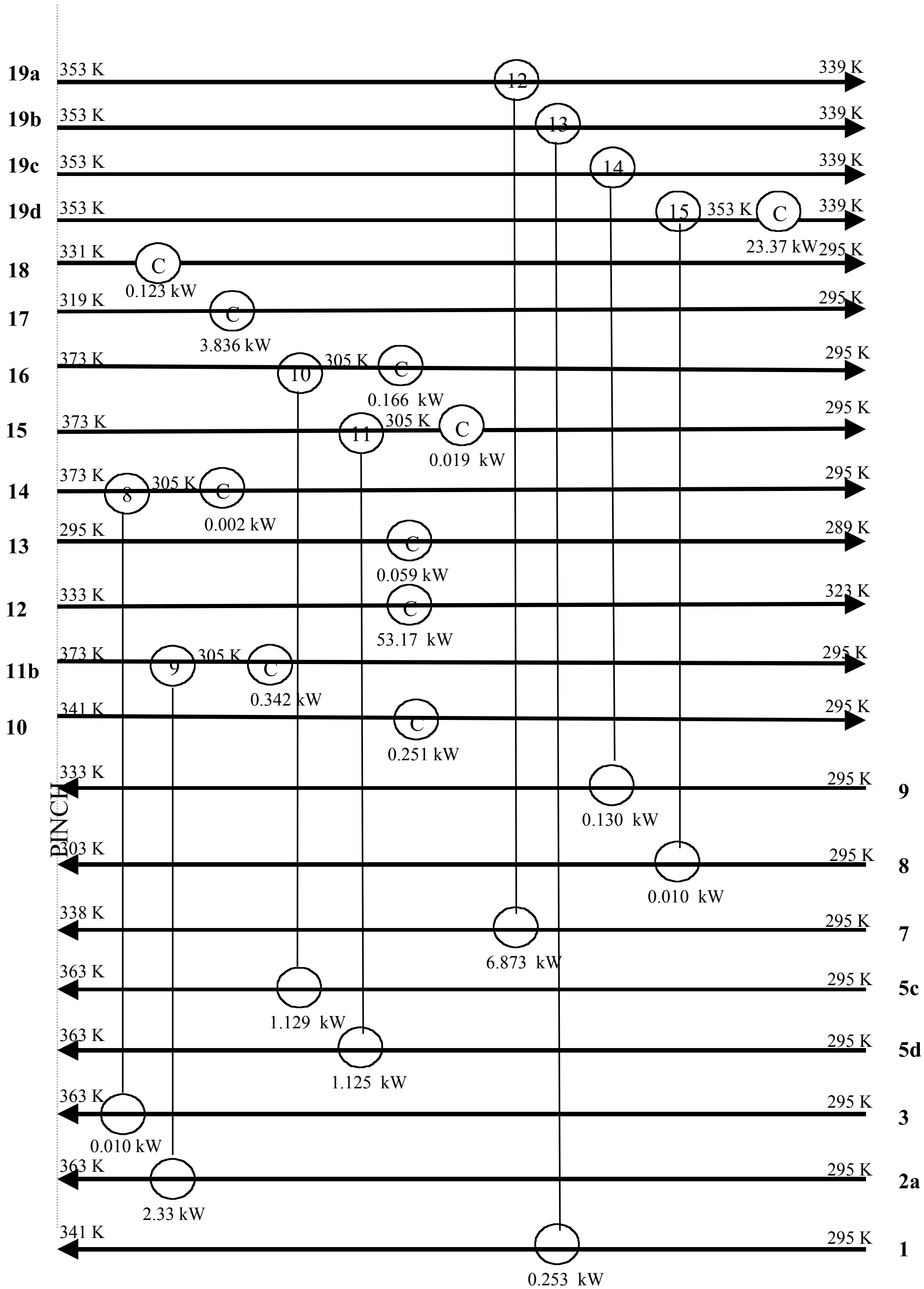


Figure 4. Heat Exchanger Network for Below the Pinch.

7.3 Heat Exchanger Sizing

The size of the heat exchange equipment that is required for a given design is a function of the heat exchanger area, A. The heat load, Q, and the effective temperature difference, ΔT, can be used to calculate heat exchanger area, where $A = (1/U)*(Q/\Delta T)$.

The overall heat transfer coefficient, U, will vary with fluid enthalpy and velocity. Order-of-magnitude estimates can be made for U in order to estimate heat exchanger area. Many heat transfer textbooks give typical ranges for U. The range of U for a water-to-water heat exchanger varies from approximately 850 W/m^2-K up to 2500 W/m^2-K (Bejan, 1993; Welty et al; Perry and Chilton, 1973). The range of U for an air-to-water or air-to-air heat exchanger varies from approximately 10 W/m^2-K up to 280 W/m^2-K (Bejan, 1993; Welty et al; Perry and Chilton, 1973). For the purposes of this investigation, a value of 1000 W/m^2-K will be used for all water-to-water heat exchangers, and a value of 50 W/m^2-K will be used for all air-to-water heat exchangers.

For heat exchangers that utilize purely counter-current flow, which is a simplifying assumption in this investigation, the effective temperature difference, is simply equal to the logarithmic mean temperature difference, ΔT_{LM}. The value for ΔT_{LM} is calculated according to Equation 1. In equation 1, the subscripts *1* and *2* denote the hot and cold fluid, respectively, and the subscripts *i* and *o* denote the inlet and outlet, respectively.

$$\Delta T_{LM} = \frac{(T_{1i} - T_{2o}) - (T_{1o} - T_{2i})}{\ln[(T_{1i} - T_{2o})/(T_{1o} - T_{2i})]}$$

Table 37 lists each heat exchanger and its calculated area for the example system, as the heat exchangers are numbered in Figures 3 and 4.

Table 37. Heat Exchanger Thermal Characteristics for the Example System.

Heat Exchanger Number	Q (kW)	U (W/m^2-K)	ΔT (K)	A (m^2)
1	0.102	50	10.00	0.204
2	0.005	50	10.00	0.010
3	0.342	1000	14.83	0.023
4	0.460	1000	21.00	0.022
5	0.209	50	10.00	0.418
6	0.358	50	10.49	0.682
7	1.676	50	10.00	3.352
8	0.010	50	10.00	0.020
9	2.33	1000	10.00	0.233
10	1.129	50	10.00	2.258
11	1.125	50	10.00	2.250
12	6.873	50	26.95	5.101
13	0.253	50	24.63	0.205
14	0.130	50	30.44	0.085
15	0.010	50	53.85	0.004

In order to estimate the mass and volume of each heat exchanger and related equipment, a simplified estimate of required heat exchanger masses and volumes has been made. It is assumed that each heat exchanger is a cylindrical single-pass shell and tube-type of exchanger made of carbon steel having a density of 7.842×10^{-3} kg/cm^3. Table 38 lists the assumed shell inside diameter, tube outside diameter, number of tubes, wall thickness and shell length for each heat exchanger. Table 39 lists the mass of the tubes, shell mass, an estimate of the mass of related connections and equipment and the total mass. The additional mass is estimated simply as being equal to that of the shell mass. Table 40 lists the calculated shell volume, estimated volume of related connections and equipment, and the total volume.

Table 38. Heat Exchanger Geometric Characteristics for the Example System.

Heat Exchanger Number	Shell Inside Diameter (cm)	Tube Outside Diameter (cm)	Number of Tubes	Wall Thickness (cm)	Shell Length (m)
1	8	1.0	9	0.2	0.72
2	4	1.0	1	0.2	0.32
3	4	1.0	1	0.2	0.73
4	4	1.0	1	0.2	0.70
5	10	1.0	16	0.2	0.83
6	10	1.0	16	0.2	1.36
7	30	1.6	50	0.2	1.33
8	4	1.0	1	0.2	0.64
9	8	1.0	9	0.2	0.82
10	30	1.6	50	0.2	0.90
11	30	1.6	50	0.2	0.90
12	40	1.6	90	0.2	1.13
13	8	1.0	9	0.2	0.73
14	8	1.0	9	0.2	0.30
15	4	1.0	1	0.2	0.12

Table 39. Estimated Mass of Heat Exchangers and Related Equipment.

Heat Exchanger Number	Mass of Tubes (kg)	Shell Mass (kg)	Estimated Additional Mass (kg)	Total Mass (kg)
1	3.20	2.844	2.844	8.89
2	0.16	0.627	0.627	1.41
3	0.36	1.447	1.447	3.26
4	0.34	1.374	1.374	3.09
5	6.56	4.097	4.097	14.75
6	10.70	6.689	6.689	24.08
7	52.57	19.72	19.72	92.00
8	0.31	1.255	1.255	2.82
9	3.65	3.248	3.248	10.15
10	35.41	13.28	13.28	61.98
11	35.29	13.23	13.23	61.76
12	80.00	22.22	22.22	124.5
13	3.22	2.864	2.864	8.95
14	1.34	1.191	1.191	3.72
15	0.06	0.233	0.233	0.52
Total Mass (kg)				421.8

Table 40. Estimated Volume of Heat Exchangers and Related Equipment.

Heat Exchanger	Shell Volume (m^3)	Estimated Additional	Total Volume

Number		Volume (m^3)	(m^3)
1	0.015	0.015	0.029
2	0.002	0.002	0.003
3	0.004	0.004	0.007
4	0.004	0.004	0.007
5	0.026	0.026	0.052
6	0.043	0.043	0.085
7	0.377	0.377	0.754
8	0.003	0.003	0.006
9	0.017	0.017	0.033
10	0.254	0.254	0.508
11	0.253	0.253	0.506
12	0.567	0.567	1.134
13	0.015	0.015	0.029
14	0.006	0.006	0.012
15	0.001	0.001	0.001

8 Cost Assessment in Terms of Equivalent System Mass

Heat exchanger mass and volume may be used to calculate the equivalent system mass (ESM) for each unit. The cost of each heat exchanger in terms of mass and volume may be weighed against the quantity of power and cooling that is saved, also in terms of ESM.

In order to estimate the equivalent system mass cost and savings of the heat exchangers and related equipment, cost factors for power, cooling, and volume must be chosen. The Advanced Life Support Research and Technology Development Metric Document (LMSMSS 33045) is used to determine the cost factors to apply to this example system.

The underlying mission upon which the ALS Research and Technology Development Metric is based is that of the Design Reference Mission of the NASA Mars Exploration Study Team (Hoffman and Kaplan, 1997, and Drake, 1998). The power, heat rejection and volume cost factors that were developed for that mission while in transit and on the Martian surface are applied here. For this investigation, the transit trip will be assumed to take 180 days per leg, resulting in a total duration of 360 days. The surface mission will be assumed to last for 540 days (Drysdale and Hanford, 1999).

As in Hanford and Drysdale 1999, during transit, an ISS common module-type rigid shell is incorporated. During the surface stay, a TransHab-type inflatable structure with 19 cm of water for storm shielding is used. During transit, power is provided by conversion of solar energy to electricity with photovoltaic cells. On the Martian surface, Brayton conversion from a nuclear power plant of the SP100 class generates 100 kW of power continuously. A lightweight, inflatable heat rejection system is used during both transit and the surface stay. The differences in the thermal environment between interplanetary space and the Martian atmosphere results in a difference in heat rejection cost factors. Table 41 lists the cost factors used in this document for transit and surface portions of the mission.

Table 41. Cost Factors for Transit and Surface Portions of Mission, from Hanford and Drysdale, 1999.

Cost Factor	Transit	Surface
Volume (m^3/kg)	0.015	0.062
Power (W/kg)	12	18
Heat Rejection (W/kg)	47.5	15

Table 42 shows the equivalent system mass cost in terms of mass and volume and savings in terms of power and cooling for the transit portion of the mission for each heat exchanger. Table 43 shows the equivalent system mass cost in terms of mass and volume and savings in terms of power and cooling for the surface portion of the mission for each heat exchanger.

Table 42. Equivalent System Mass Comparisons for the Transit Portion of the Mission for the Example System.

Heat Exchanger Number	Mass (kg)	Volume ESM (kg)	Power ESM (kg)	Cooling ESM (kg)	ESM Increase (kg)	ESM Decrease (kg)	ESM Savings (kg)
1	8.888	1.934	8.500	2.147	10.82	10.65	-0.174
2	1.412	0.213	0.417	0.105	1.625	0.522	-1.103
3	3.256	0.492	28.50	7.200	3.748	35.70	31.95
4	3.092	0.467	38.33	9.684	3.559	48.02	44.46
5	14.75	3.483	17.42	4.400	18.23	21.82	3.583
6	24.08	5.687	29.83	7.537	29.77	37.37	7.601
7	92.00	50.28	139.7	35.28	142.3	175.0	32.67
8	2.823	0.427	0.833	0.211	3.250	1.044	-2.206
9	10.15	2.209	194.2	49.05	12.36	243.2	230.9
10	61.98	33.87	94.08	23.77	95.85	117.9	22.01
11	61.76	33.75	93.75	23.68	95.51	117.4	21.93
12	124.4	75.57	572.8	144.7	200.0	717.4	517.4
13	8.951	1.948	21.08	5.326	10.90	26.41	15.51
14	3.721	0.810	10.83	2.737	4.531	13.57	9.039
15	0.524	0.079	0.833	0.211	0.603	1.044	0.440
Total (kg)	421.8	211.2	1251	316.0	633.1	1567	934.0

Table 43. Equivalent System Mass Comparisons for the Surface Portion of the Mission for the Example System.

Heat Exchanger Number	Mass (kg)	Volume ESM (kg)	Power ESM (kg)	Cooling ESM (kg)	ESM Increase (kg)	ESM Decrease (kg)	ESM Savings (kg)
1	8.888	0.468	5.667	6.800	9.356	12.47	3.111
2	1.412	0.052	0.278	0.333	1.463	0.611	-0.852
3	3.256	0.119	19.00	22.80	3.375	41.80	38.42
4	3.092	0.113	25.56	30.67	3.205	56.22	53.02
5	14.75	0.843	11.61	13.93	15.59	25.54	9.951
6	24.08	1.376	19.89	23.87	25.46	43.76	18.30
7	92.00	12.16	93.11	111.7	104.2	204.8	100.7
8	2.823	0.103	0.556	0.667	2.926	1.222	-1.704
9	10.15	0.534	129.4	155.3	10.69	284.8	274.1
10	61.98	8.194	62.72	75.27	70.17	138.0	67.82
11	61.76	8.165	62.50	75.00	69.92	137.5	67.58
12	124.4	18.28	381.8	458.2	142.7	840.0	697.3
13	8.951	0.471	14.06	16.87	9.422	30.92	21.50
14	3.721	0.196	7.222	8.667	3.917	15.89	11.97
15	0.524	0.019	0.556	0.667	0.543	1.222	0.679
Total (kg)	421.8	51.101	834.0	1001	472.9	1835	1362

The heat exchangers will require crew time for cleaning and general maintenance. If it is assumed that all heat exchangers are incorporated into the mission except for those that do not prove to be economical in Table 42 and Table 43, and the crew time cost of maintenance is approximately 0.1 hours/m^2/year, then the total crew time requirement for the heat exchangers is 1.47 hours for the transit portion and 2.20 hours for the surface portion. This is equivalent to 4.78 x 10^{-3} hours per week per person for the transit portion and 4.77 x 10^{-3} hours per week per person for the surface portion.

The cost of the crew time in terms of ESM is calculated with the following equation.

$$ESM_{ct} = ESM_{t} - ESM_{w/oct} = ESM_{w/oct}\left(\left(\frac{t_t}{t_t - t_{als}}\right) - 1\right)$$

In Equation 2, ESM_{ct} is the crew time portion of the equivalent system mass for the entire system, ESM_t is the total equivalent system mass for the entire system, $ESM_{w/oct}$ is the equivalent system mass without ESM_{ct}, t_t is the total time allotted for work per week during the mission, and t_{als} is the total time spent maintaining the ALS per week during the mission.

In Hanford and Drysdale 1999, 136.5 hours per year for ALS maintenance are calculated for a crew of 6. This results in t_{als} of 0.437 hours per week per person. If the time required for heat exchanger maintenance is also considered, t_{als} is 0.442 hours per week per person. It will be assumed that 66 hours per week per person are allotted for work during the transit and surface portions of the mission.

In Hanford and Drysdale 1999, the $ESM_{w/oct}$ is calculated as 59,576 kg for the two transit legs and 16,062 kg for the surface portion. The ESM_{ct} without use of the heat exchangers is thus 397.1 kg for the transit portion and 107.1 kg for the surface portion. The ESM_{ct} with incorporation of the heat exchangers for the transit portion is 401.7 kg, and ESM_{ct} for the surface portion is 108.3 kg. Thus, the increase in the crew time portion of equivalent system mass from incorporation of the heat exchangers is 4.6 kg for the transit portion and 1.2 kg for the surface portion.

9 Discussion

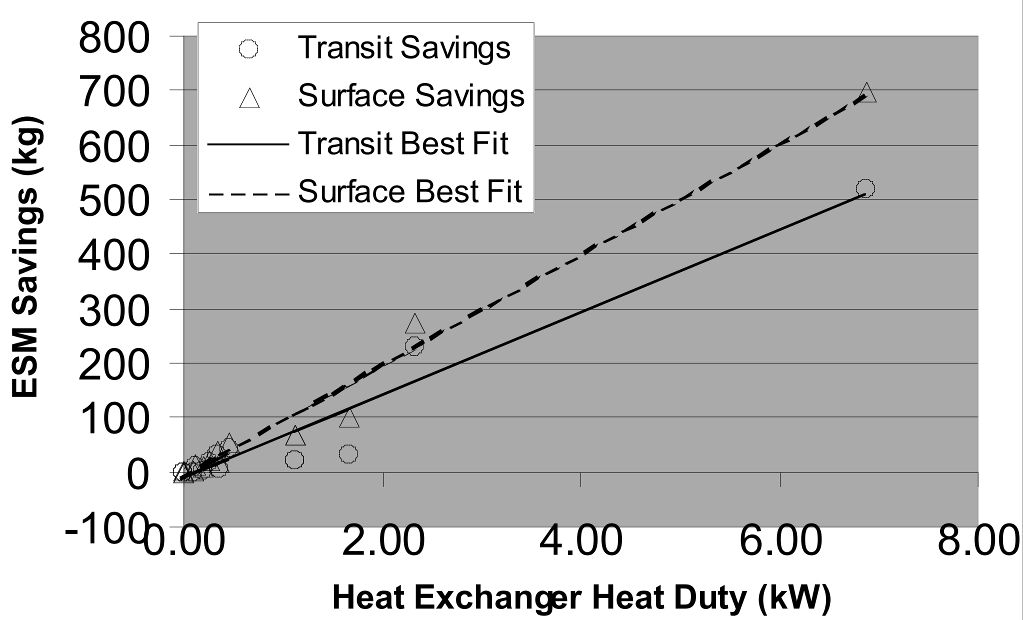
Table 42 shows that heat exchangers #1, #2, and #8 do not result in an ESM savings for the transit portion of the mission, and Table 43 shows that heat exchangers #2 and #8 do not result in an ESM savings for the surface portion of the mission.

A linear least-squares linear fit of transit savings versus heat exchanger heat duty, as shown in Figure 5, estimates the ESM savings as a function of exchanger heat duty according to Equation 2 ($R^2 = 0.93$). A linear least-squares linear fit of surface savings versus heat exchanger heat duty, also shown in Figure 5, estimates the ESM savings as a function of exchanger heat duty according to Equation 3 ($R^2 = 0.97$). In Equation 2 and 3, ESM Savings has units of kg, and Q, heat duty, has units of kW. These equations suggest that with the assumptions made for this investigation, heat exchangers prove to be economical in terms of ESM if they exchange at least 0.18 kW during transit or 0.11 kW during the surface stay.

Transit Savings Equation: ESM Savings = 75.80 * Q – 13.59 Equation 2

Surface Savings Equation: ESM Savings = 101.9 * Q – 11.23 Equation 3

Figure 5. ESM Savings versus Heat Duty



Because of the extensive simplifying assumptions that were made in estimation of heat exchanger mass and volume, it is important to note that these predictions are preliminary. The estimates do give a general idea of the order of magnitude of heat exchange that is worthwhile in terms of ESM.

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11 Acronyms and Abbreviations

A	Heat exchanger area (m^2)
AES	Air Evaporation System
ALS	Advanced Life Support
APCOS	Aqueous-Phase Catalytic Oxidation System
ARC	Ames Research Center
ARS	Atmosphere Revitalization System
BIO-Plex	Bioregenerative Planetary Life Support Systems Test Complex
BPC1	Biomass Production Chamber #1
BVAD	Baseline Values and Assumptions Document
C_p	Heat capacity at constant pressure (kJ/kg-K)
Cp_{cold}	Heat Capacity Flowrate for a Cold Stream (kW/K)
Cp_{hot}	Heat capacity flowrate for a hot stream (kW/K)
CO_2	Carbon dioxide gas
CTSD	Crew and Thermal Systems Division
$C_2H_6O_2N_2$	Urine solids
C_4H_5ON	Protein (edible or inedible)
$C_6H_{12}O_6$	Carbohydrate
$C_6H_{10}O_5$	Fiber
$C_{10}H_{11}O_2$	Lignin
$C_{13}H_{28}O_{13}N_2$	Sweat solids
$C_{16}H_{32}O_2$	Fat
$C_{42}H_{69}O_{13}N_5$	Feces solids
ESM	Equivalent System Mass (kg)
ESM_{ct}	Crew-time portion of Equivalent System Mass (kg)
ESM_t	Equivalent System Mass of the entire system (kg)
$ESM_{w/oct}$	Equivalent System Mass without accounting for crew time (kg)
FPS	Food Processing System
HNO_3	Nitric acid
HPS	High-Pressure Sodium
HVAC	Heating, Ventilation and Air Conditioning
H_2	Hydrogen gas
H_2O	Water
ICES	International Conference on Environmental Systems
JSC	Johnson Space Center
KSC	Kennedy Space Center
LMLSTP	Lunar-Mars Life Support Test Project

NASA	National Aeronautics and Space Administration
N_2	Nitrogen gas
O_2	Oxygen gas
PPF	Photosynthetic Photon Flux
Q	Heat load (kW)
SAE	Society of Automotive Engineers
SMAP	Systems Modeling and Analysis Project
SPS	Solids Processing System
TCCS	Trace Contaminant Control System
T_{1i}	Temperature of hot side fluid at inlet (K)
T_{1o}	Temperature of hot side fluid at outlet (K)
T_{2i}	Temperature of cold side fluid at inlet (K)
T_{2o}	Temperature of hot side fluid at outlet (K)
t_{als}	Time spent on maintenance of the ALS system (hours/week-person)
t_t	Total time allotted for work (hours/week-person)
U	Heat transfer coefficient (kW/m^2-K)
WRS	Water Recovery System
_T	Effective temperature difference for heat exchange (K)
ΔT_{LM}	Logarithmic mean temperature difference (K)
$\_T_{min}$	Minimum temperature difference required between a hot and cold stream in order for heat exchange to occur (K)

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1 Introduction

The systems modeling and analysis group at Ames Research Center is currently working on the first year tasks for the grant entitled "Advanced Life Support Power Reduction." The research involves developing approaches for reducing system power and energy usage in Advanced Life Support (ALS) regenerative systems suitable for exploring the Moon and Mars. The effects of system configuration and processor scheduling are being investigated, along with system energy integration and energy reuse techniques and advanced control methods for efficient distribution of power and thermal resources.

1.1 Motivation

This research addresses the issues of optimization of mass and power. Equivalent system mass has been called out as a key metric for evaluating the cost of launching and operating life support systems. Emplaced mass, resupply mass, power consumption and volume are all elements of the equivalent system mass. Because of the high energy requirements associated with closed regenerative system operation, research to reduce power loads and increase thermal energy efficiency is extremely important for reducing equivalent system mass. This work focuses on methods of active resource management for improved energy use and efficiency.

1.2 Year One Goals and Tasks

The year one goal of the dynamic resource allocation work is to develop a simulation model of an example life support subsystem and apply advanced control techniques to the problem of resource allocation. Specific tasks for the first year include:

1. Identify a set of resource allocation objectives for a regenerative life support system, using the JSC ALS Systems Integrated Test Bed (also known as BIO-Plex) as a baseline system.

2. Develop a simulation model of an example subsystem, such as the Air Revitalization Subsystem (ARS).

3. Evaluate various techniques and develop a controller to satisfy the resource allocation objectives identified above for the target subsystem.

1.3 Current Status

Progress has been made on all three tasks above. The remainder of this report documents our progress, and has the following structure. First, we will discuss resource allocation objectives. Second, we introduce the model of our example subsystem, which comprises both mass dynamics and power usage models. Each component is examined individually. Third, the details of the power management structure will be presented. Simulation results will then be presented, followed by a discussion and conclusions

2 ALS System Resources

Resources that make up an Advanced Life Support system include: mass resources (air, water, food), energy resources (electrical power, thermal energy), space resources (storage, free area for planting), information resources (measurement signals, computing power), and of course the time in which to do everything that needs to be done. We may have some flexibility in the use of certain of these resources during the operation of the ALS, but our access to others may be fixed or constrained (a fixed number of plant chambers, limited crew labor time, for example). Among those resources over which we can expect to have some operational discretion are energy and mass. This document describes an investigation into the use of advanced control techniques to actively manage power and mass resources. In a companion study, thermal energy considerations are being used to investigate potential system efficiency gains achieved through reuse of waste heat (see the section entitled "Application of the Pinch Technique to an Advanced Life Support System with Partial Food Production and Partial Waste Recycling Under Steady-State Conditions").

Power usage in ALS systems will vary with scheduling, disturbances, etc. These variations in power usage may be quite severe (i.e., cause surges or spikes). While the power plant may have some ability to deal with surges (e.g., photo-voltaic with batteries), over-capacity is both expensive in terms of system equivalent mass, and does nothing to address the fundamental question of excessive demand. Because the power unit must be sized to accommodate the largest demand, avoiding power spikes has the potential to reduce the required size of the power plant while at the same time increasing the dependability of the system. In order to eliminate power surges, we propose to actively manage the power distributed to system processors. Power consumption is actively monitored, and power delivery to individual processes is adjusted to avoid exceeding system power capacity. The strategy adopted must be consistent with the life support requirements of the overall system and its components.

2.1 Resource Allocation Objectives

Our objective is to smooth the demand for power throughout the system while meeting a tolerance constraint on mass resources. The tolerance specifies a range within which the state of each process and/or buffer must remain. The tolerance constraint provides us with the ability to decrease power to certain processes when necessary in order to smooth the overall system power usage, while maintaining adequate life support function. The work thus far has concentrated on developing an approach in the context of the ALS system air loop.

2.2 Approach

We envision a hierarchical management structure. To date we have examined a hierarchy comprising two levels. On the lower level, controllers will manage processes, determining the ideal or desired power for each. If overall demand exceeds supply, a higher level manager limits power delivered to individual processes. This strategy can be termed "surge" management. Under this limited power condition, a redistribution of power among currently operating processes is necessary, but not at the expense of life support function. Those processes that are well within tolerance will be expected to give up power, while those closer to criticality will not. Details of our approach are given below.

Active management of power as described here should not be regarded as a substitute for extensive *a priori* planning and/or scheduling. Planning and/or scheduling is the preferred method for smoothing power consumption, since one would like to know, to the extent possible, the level of power that will be available to each process. Under active power management, power available is unknown *a priori*; active power management will lead to some compartments getting less power than expected. Although an active power management strategy should protect the system's life support mission, poor scheduling and/or significant disturbance events nonetheless can jeopardize the function of one or more processors, or even the entire system, by limiting the power options available to the management system (see for example section 3.1.5, case 3 and section 5.1).

Active power management is a strong argument for the use of dynamic system studies. Dynamic system studies are the only way in which the consequences, with regard to life support function, of various power management strategies can be investigated. This study complements results of previous dynamic studies, which pointed out the need for flexibility in the operation of individual processors [Averner *et al.*, 1984] [Babcock *et al.*, 1984], and current carbon dioxide use smoothing analyses [Jones *et al.*, 1999]. In order to balance both mass and power in the face of dynamic system loads, and in order to recover from inevitable disturbances and failures, mass flows between processes will necessarily be modified. Power management requires similar flexibility at the level of individual components, both in order to realize power sharing and to accommodate the resulting disturbances to mass flows.

3 Model Description

We investigate the feasibility of our approach to power management using a dynamic model of a candidate BIO-Plex system design. Our current efforts have focused on the air loop. The major components include the crew, the SPS, the ARS, and the BPC. Also modeled are the crew and BPC atmospheres. Refer to Figure 1. The waste and water loops are not fully modeled, but the interface between the ARS, SPS and the WRS is in place in our model: water used by the ARS and the waste used by the SPS are tracked. Nutrient flow to the BPC and water from the crew chamber are not part of the current model. The model includes mass dynamics as well as power usage models for individual components.

3.1 Subsystem Mass Dynamics

The subsystem models capture the system mass dynamics. The mass dynamics are based on an hourly average for each flow. The state variables are mass of carbon dioxide, oxygen and N_2 in mols. This model assumes no leakage. Thus the quantity of N_2 in the system is constant. The change in molar mass in any component is given by the difference in input to output mass flow rates of each compound, plus reaction terms. See the documentation by C. Finn [1999].

3.1.1 Crew

In this model the crew and incinerator (SPS) share an atmosphere. We assume a crew size of four people. The oxygen consumption of the crew is modeled as a fixed function of time. The crew assimilates oxygen at the nominal rate of 0.84 kg per day per person [Wieland 1994]. We model variations in their activity using a sine function, with oxygen consumption higher in the "daytime" hours and lower in the "nighttime" hours. The respiration quotient is set to 0.843 mols carbon dioxide expelled for every mole of oxygen consumed. These values were determined based on composition data and reaction stochiometry given in Finn [1999] and agree with Wieland [1994].

3.1.2 SPS

The SPS processes human feces and plant waste, and is used to maintain the carbon dioxide storage tank level. A tank supplies the BPC with carbon dioxide. As a simplification, we assume that the composition of the waste stream fed to the SPS is constant. Previous simulations [Finn, 1999] are used to predict the SPS gas exchange ratios for a typical waste stream: every mol of waste burned requires 52.75 mols oxygen, and produces 42 mols of carbon dioxide and 2.5 mols of N_2. The incinerator processes waste as necessary in order to maintain the carbon dioxide tank level in the ARS, and therefore uses varying amounts of oxygen.

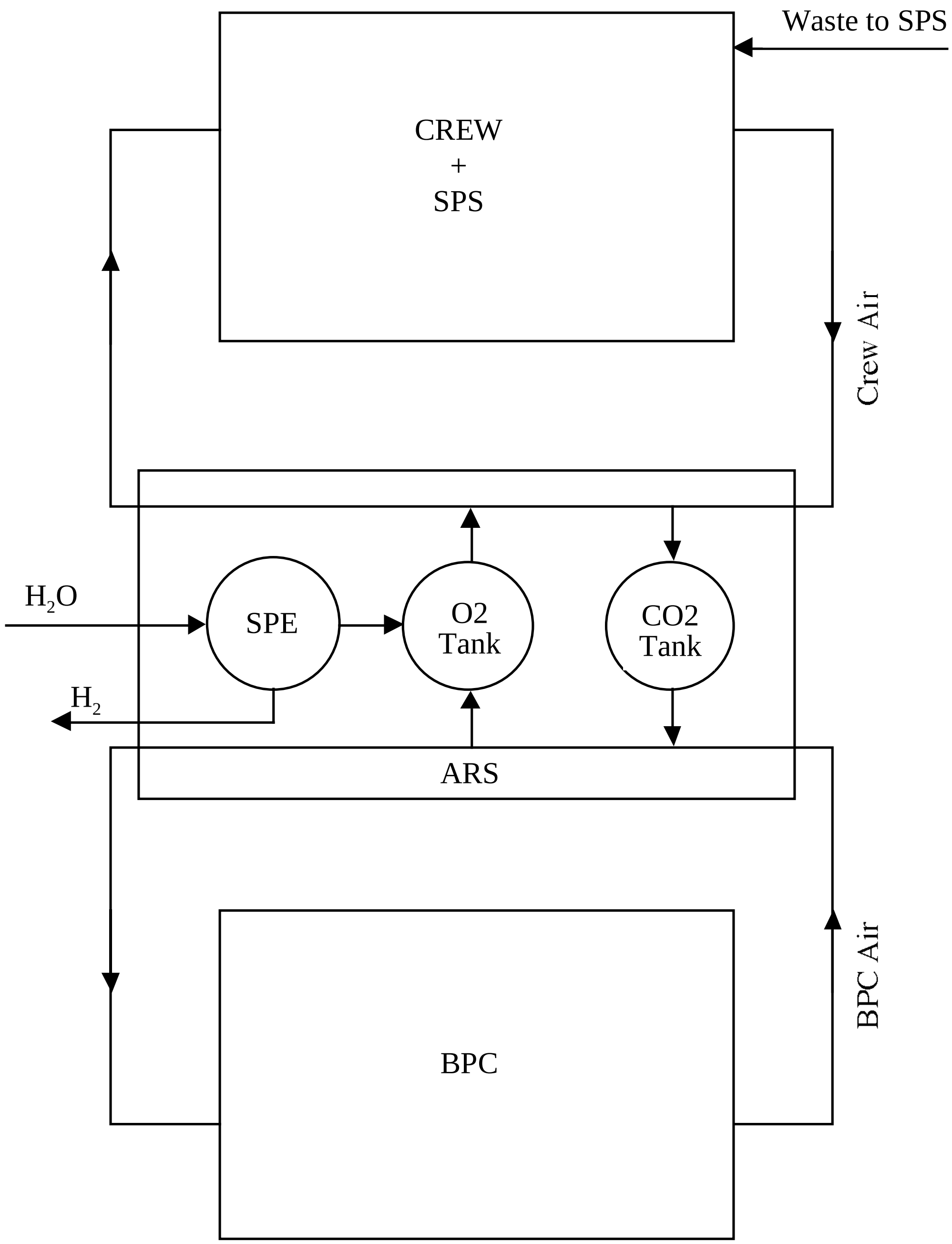

Figure 1. System model

3.1.3 ARS

Tanks for the storage of carbon dioxide and oxygen are modeled in the ARS compartment. The ARS includes carbon dioxide and oxygen scrubbers to remove these compounds from the crew atmosphere and the BPC atmosphere respectively, as well as an oxygen generator to replenish the oxygen tank through electrolysis of water as necessary.

3.1.4 BPC Crop Model

The BPC model used in this example is based on a past model developed by Ames Research Center for modeling the system dynamics of the BIO-Plex. This past model is documented in the modeling section of the ARC Advanced Life Support Analysis web page at http://joni.arc.nasa.gov/index.shtml. The BPC model includes crop growth dynamics for nine of the ten crop trays that comprise a single BPC module for the BIO-Plex. The characteristics of the nine trays are shown below in Table 1. The tenth tray, not currently modeled, is a tray of mixed greens which is continuously harvested.

Table 1. Crop Growth Parameters for the Nine Crop Trays

Crop	Planting Area, m^2	Nominal Light Level µmol/m^2-sec	Photoperiod, hrs/day	Life Cycle, days	Average Gas Exchange Ratio
Wheat	14.0	2080	20	78	1.18
Wheat	5.1	2080	20	78	1.18
Rice	14.0	1200	16	100	1.18
Soybean	14.0	1000	12	90	1.319
Soybean	14.0	1000	12	90	1.319
Peanut	5.1	600	16	118	1.317
Peanut	5.1	600	16	118	1.317
Potato	8.2	725	16	147	1.13
Potato	8.2	725	16	147	1.13

The carbon fixation profile for each of the nine crop trays was modeled based on a slightly modified Energy Cascade Model similar to that in Volk, Bugbee and Wheeler (1995). The relationships for A and Q are replaced by monod functions in order to remove the discontinuities, and the constant Q_{max} has been replaced by a monod function in order to make crop growth a function of carbon dioxide concentration inside the BPC chamber. The parameters A_{max}, Q_{min}, Q_{max}, C, t_a, t_q and t_m describe the general behavior of each crop. And the parameters age, co2_ppm, area, $PPF_{nominal}$ and PPF_{actual} describe the growing conditions inside each of the crop trays. The following set of equations was used for determining the net photosynthetic rate of each tray of crops.

$P_n = P_g - R$

$P_g = 0.0036*area*Q*A*PPF_{actual}$
$R = 0.0036*(1-C)*area*Q*A*PPF_{nominal}$

C = 0.32
area = from Table 1
$PPF_{nominal}$ = from Table 1
PPF_{actual} = from simulation

$Q = Q_{min} + (Q_{max} - Q_{min})*(t_m - age)/((t_m - t_q)^\wedge 15+ (t_m - age)^\wedge 15)^\wedge(1/15)$

age = from simulation
co2_ppm = from simulation
t_m = life cycle from Table 1
$t_q = 33$
$Q_{min}=0.01$
$Q_{max}=0.066*co2\_ppm/(210^\wedge 1.4+co2\_ppm^\wedge 1.4)^\wedge(1/1.4)$

$A = A_{max}*age/(t_a^\wedge 5+age^\wedge 5)^\wedge(1/5)$

$t_a=12.0$
$A_{max}=0.93$

where

P_n = net photosynthesis, mol CO_2/hr
P_g = gross photosynthesis, mol CO_2/hr
R = respiration, mol CO_2/hr
C = carbon use efficiency
area = planting area, m^2
$PPF_{nominal}$ = time averaged (over the photoperiod) photosynthetic photon flux,

μmol/m^2-sec
PPF_{actual} = actual instantaneous photosynthetic photon flux, μmol/m^2-sec
Q = canopy quantum yield, mol carbon/mol PPF
Q_{min} = minimum canopy quantum yield, mol carbon/mol PPF
Q_{max} = maximum canopy quantum yield, mol carbon/mol PPF
A = fraction of PPF absorbed by canopy
A_{max} = maximum fraction of PPF absorbed by canopy
age = time since initial planting, days
t_a= time of canopy closure, days
t_q = time of onset of senescence, days
t_m = time at crop maturity, days
co2_ppm = carbon dioxide level in the BPC atmosphere, ppm

The net photosynthesis defined above gives the net moles of carbon fixed per hour. Carbon fixation is positive during the light cycle provided that light levels are sufficiently high so that photosynthesis dominates over respiration. During the dark cycle, no photosynthesis occurs, only dark respiration, and the carbon fixation rate is negative. The length of the light cycle is given by the photoperiod, which is shown in Table 1 for the nine crop trays.

The carbon fixation rate for each crop tray contributes to the overall gas exchange rate for all nine crop trays. For every mole of carbon fixed, one mole of carbon dioxide is consumed by the crops. The carbon dioxide uptake rate for each crop tray is simply equal to the net carbon fixation rate. For every mole of carbon dioxide that is fixed, a certain amount of oxygen is produced. The amount of oxygen produced is dependent upon the composition of the material that is being grown. For the purpose of this model, we define the average gas exchange ratio to be equal to the moles of oxygen produced per mole of carbon dioxide consumed. We base this ratio on the average composition of each crop at harvest time, as discussed in the web site documentation. The carbon dioxide consumption rates are then summed together for all nine crop trays in order to produce an overall carbon dioxide usage rate by the crops. Analogously, the oxygen production rates are summed together for all nine crop trays in order to produce an overall oxygen production rate by the crops.

Also modeled as part of the BPC is the power associated with running the lights for each crop tray. The power usage for each crop tray is given by the following equations.

$$power = PPF_{actual}*area/eff$$

eff = 0.5535

where

power = power required, W
eff = light delivery efficiency, µmol/J

The total power usage by the BPC lights is just the sum of the power usage of all nine trays.

We have simulated a situation where all of the crops have been planted before the test begins, and are at varying degrees of developmental maturity. Table 2 lists the preplanting schedule used here for the nine crop trays.

Each crop tray receives light for a fixed amount of time each day (photoperiod, shown in Table 1). The photoperiods of the nine trays can either begin all at the same time or be staggered throughout the day. Table 2 shows daily schedules for the photoperiods of the nine crop trays for three test cases which will be discussed below in the BPC power management section.

Table 2. BPC preplanting and photoperiod schedules.

Crop	Preplanting, days before start of test	Photoperiod Staggering, hours before start of light period		
		Case 1	Case 2	Case 3
Wheat	1	0	0	0
Wheat	53	0	4	4
Rice	38	0	20	20
Soybean	33	0	16	16
Soybean	71	0	12	12
Peanut	47	0	8	8
Peanut	113	0	4	4
Potato	61	0	20	20
Potato	9	0	12	12

3.1.5 BPC Power Smoothing

The BPC possesses its own power management system, which distributes light power allotted to the BPC amongst the individual crop trays. Management of light power at the BPC level is deemed necessary because plant lights are an enormous power consumer, and light energy is so closely tied to crop growth and gas balance. Power management and scheduling are important for smooth dynamics, as the three test cases below will show. In case 1, none of the crop photoperiods are staggered, resulting in a worst-case power scenario. In case 2, the crop photoperiods are staggered, which helps reduce the fluctuations in the BPC power profile. In both cases 1 and 2, the light levels are maintained at the nominal PPF values throughout all of the light period. In case 3, the crop photoperiods are staggered, as in case 2. In addition, a power manager is employed to adjust the PPF levels throughout the photoperiod. The goal of the power manager is to smooth the BPC lighting power profile.

Case 1

At the beginning of each day, lights will be on for all nine trays, and the power use will be at its maximum possible level (Figure 2). Over the course of the day, lights will be turned off as each tray reaches the end of its photoperiod. At the end of each day, all of the lights will be off for all nine trays, and the power use will be at its minimum possible level. Carbon dioxide levels in the chamber will escalate during the dark period at the end of the day due to crop dark respiration. It immediately becomes clear that staggering of the crop photoperiods throughout the day is desirable, and will help to even out the power usage and crop gas exchange characteristics (Figure 3 and Figure 4).

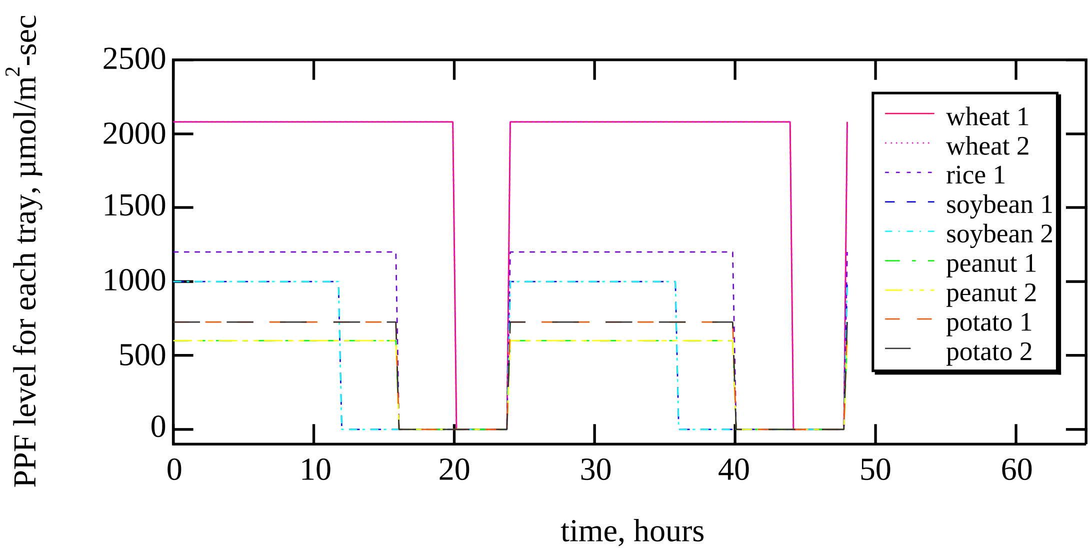

Figure 2. Light level for each tray inside the BPC for case 1.

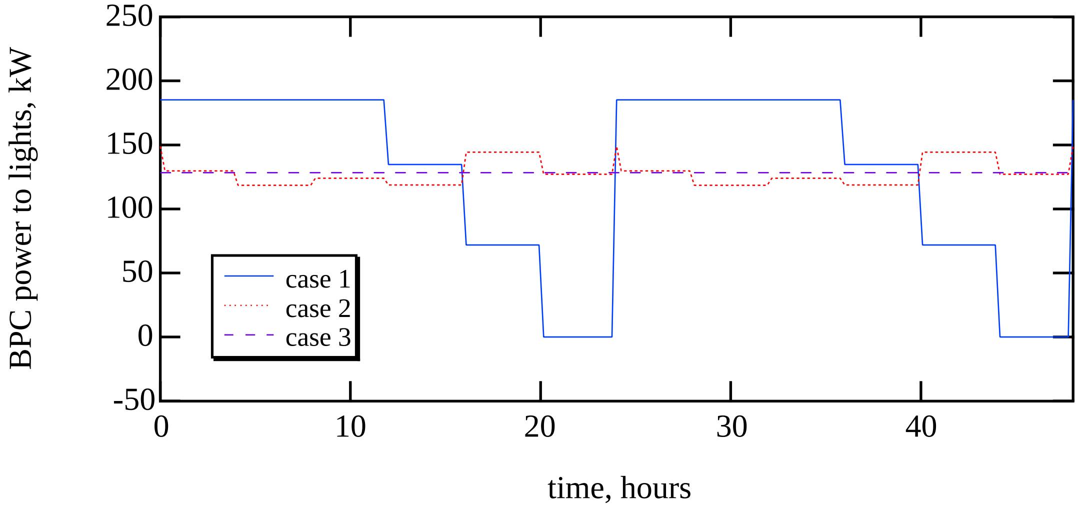

Figure 3. Total power use by all nine crop trays inside the BPC.

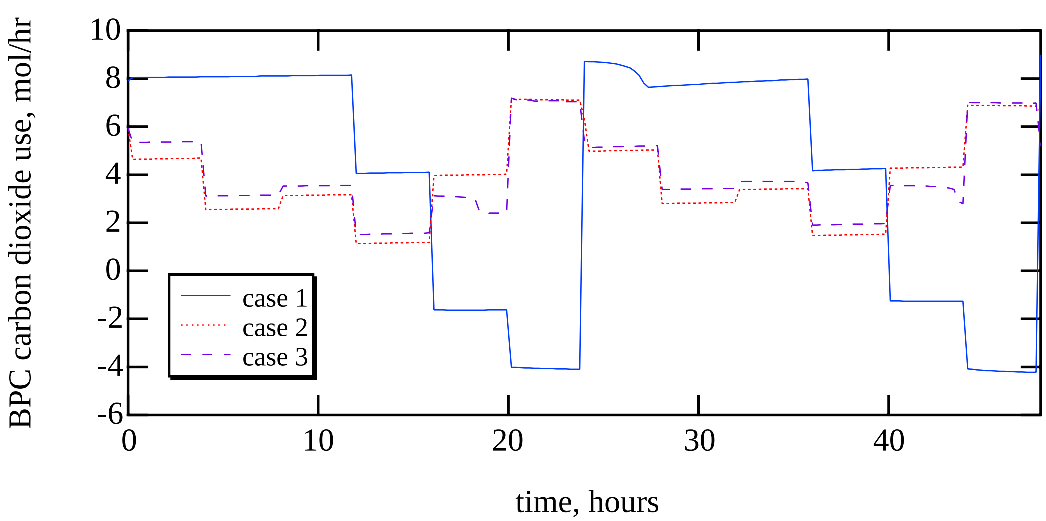

Figure 4. Total carbon dioxide use by all nine crop trays inside the BPC.

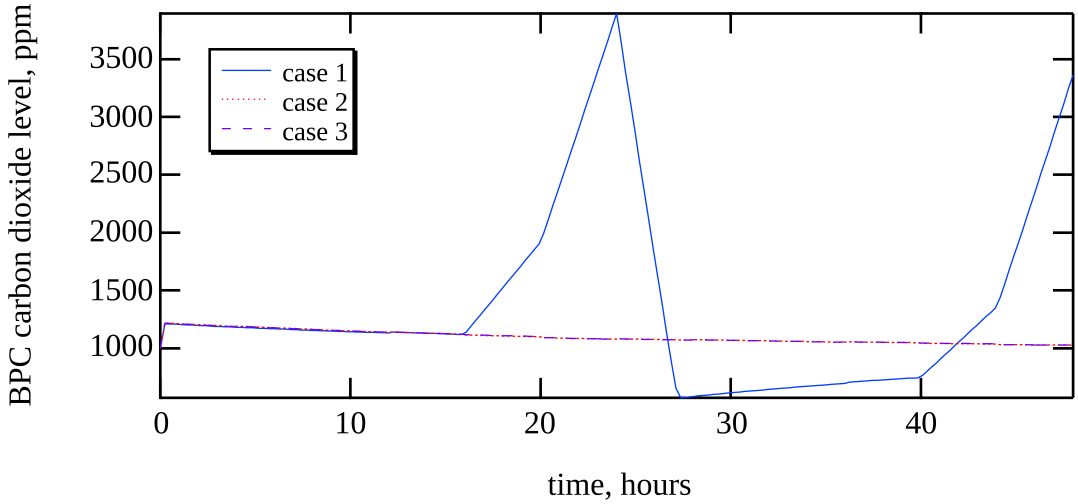

Figure 5. Atmospheric carbon dioxide level inside the BPC.

Case 2

In case 2, the photoperiods of the nine trays are staggered throughout the day, as shown in Figure 6. This scheduling results in smoother power load and gas exchange profiles (Figure 3 and Figure 4). Since lights will be on for at least some of the crop trays at all times, there will always be some photosynthesis occurring within the BPC to help offset the dark respiration of those crop trays which have their lights off (Figure 5).

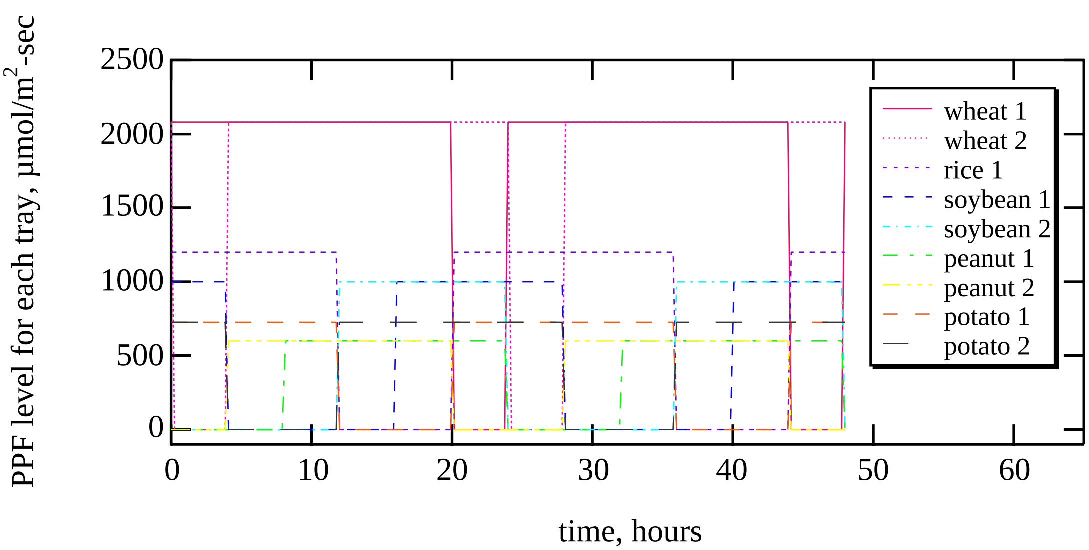

Figure 6. Light level for each tray inside the BPC for case 2.

Case 3

In case 3 the BPC is given a constant amount of power in order to demonstrate its power smoothing capability. To smooth the overall power profile, the BPC varies the light levels of individual crop trays during their light cycles, freeing up power from those that can afford it to make up for deficits suffered by other trays, Figure 7, so that the average light level of each crop (over its photoperiod) meets its nominal value ($PPF_{nominal}$). This sharing of light power between trays is possible if and only if the day and light cycle of the crops are close to a balance. If the planting schedule is such that all trays are on/off together, no such sharing can occur.

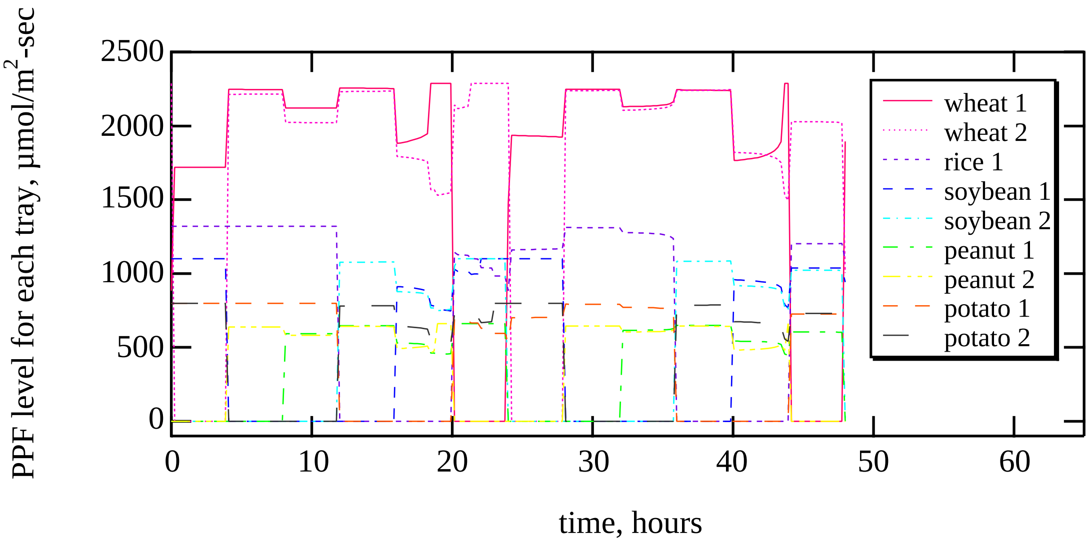

Figure 7. Light level for each tray inside the BPC for case 3.

When the BPC is integrated with the power management system, the amount of power it is allotted will depend on the overall system power load and the capacity of the power system. Thus, in order to have a chance at delivering enough light power to meet each tray's daily target value, the BPC requests power from the high level power manager based on a prediction of crop lighting requirements. While the BPC will not receive a constant amount of power (as was the case in the above example), its strategy of sharing power amongst crop trays results in an effective and efficient use of its power allotment.

For each crop tray, a target value for the amount of light which should be delivered per unit area during an entire photoperiod ($PPF_{nominal}$ * photoperiod) has been specified. At sample times during the light period (every 12 minutes) the BPC calculates how much light has already been delivered, and adds to this the amount that is expected to be delivered by the next sample period based on current light levels. Subtracting this total from the target value and dividing by the time remaining in the photoperiod at the next sample time, the BPC predicts the average light level required in order to deliver the daily target value to each tray by the end of the photoperiod (for those trays that are currently off, the BPC also predicts which will turn on in the next photoperiod, and their desired power level). The BPC sums the predicted power needs over all crop trays and requests this amount for the next sample time from the high level power manager.

In order to avoid stressing the crops, a maximum acceptable light level of 110% of nominal for each crop has been specified, where nominal light levels are as defined in Table 1. For each crop tray, the BPC power management system can vary the light level while meeting the daily target value, but must guarantee that the maximum acceptable light level is never exceeded. In order to achieve this balance, the following strategy is adopted. When the predicted average light level requirement for a crop tray reaches the maximum acceptable light level, it enters the "power critical" state. The BPC signals the high level power manger that one or more trays have become critical and submits two power level requests: the minimum amount of power required to satisfy critical trays, and the amount all trays require (both critical, and non-critical). The high level power manager always allots enough power to meet the needs of those trays in the power critical state, but reserves the right to reduce the total BPC power allotment depending on overall system power requirements. This guarantees that once trays become critical, there will be enough power to satisfy their needs.

At the current sample time, once power has been made available, the BPC delivers the required amount of power to the critical trays, and partitions any remaining power proportionately amongst the non-critical trays. In the event that the power remaining is less than or equal to the total request, the remaining power is partitioned between all of the non-critical trays proportionally. In other words, if only 80% of the requested amount is available, each non-critical crop tray receives 80% of its power request. Remaining power does not necessarily have to be distributed equally, however we have chosen this method as a simplification.

If, however, the power remaining is more than the total request, then the BPC attempts to deliver more than the requested power amount to each non-critical crop tray by increasing its PPF level. The BPC determines each tray's capacity to accept extra power based on the difference between the requested value and its maximum acceptable level. The amount of total excess capacity that the crops can take up is the sum of these. If the amount of power the BPC has left over is greater than this capacity, then it will set all of the light levels to their maximum acceptable levels but will not be able to use up its entire power allotment. If the amount of power the BPC manager has left over is less than the total excess capacity, it will partition the extra power to the trays in a proportional fashion. In other words, if the extra power available is only 50% of the total capacity to take extra power, then each tray receives extra power equal to 50% of its extra power accepting capacity. This partitioning can only occur if the high level power manager allots to the BPC more power than it requests. This is a poor power management strategy for the high level power manager to adopt, especially if it shuts down other processes in order to allot to the BPC more power than it needs or can use. Figure 8 shows the requested and allotted power for the case in which the power manager allots more power than the BPC can use. In this example, the BPC is given any power not used by the other processors, so that the power plant is always running at maximum capacity (150 kW in this case). Figure 9 shows the requested and allotted power for the case in which the BPC gets exactly the amount of power for which it asks (unless the power plant capacity of 150 kW would be exceeded).

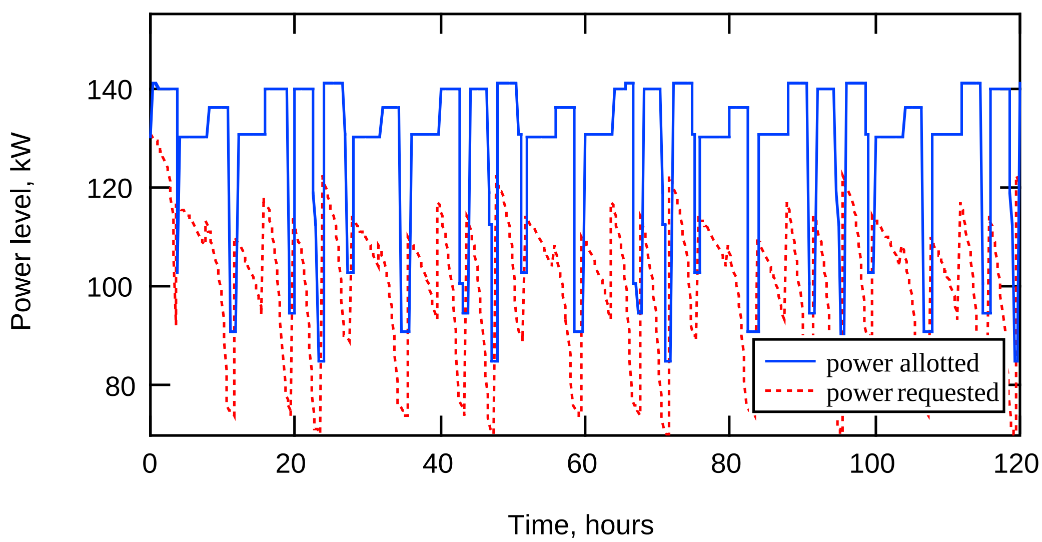

Figure 8. Requested BPC light power versus allotment exceeding request

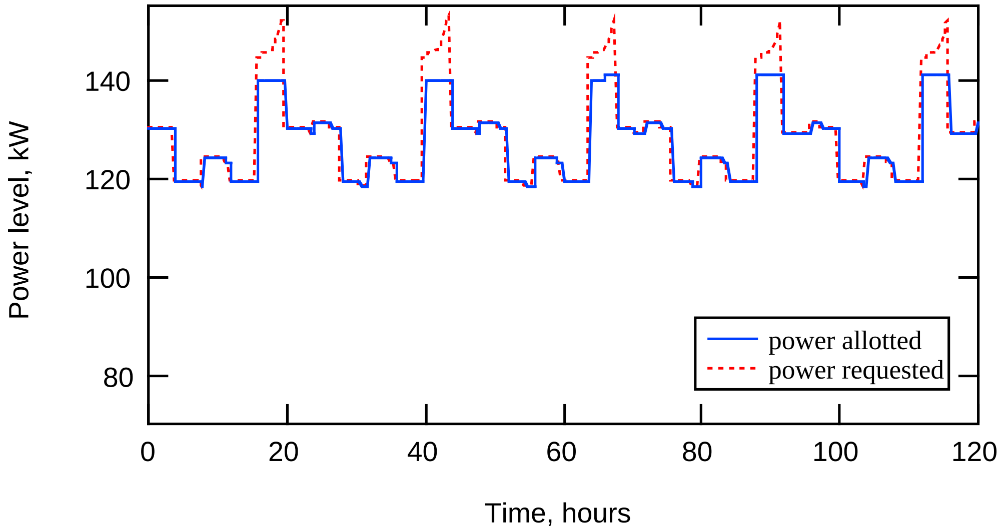

Figure 9. Requested BPC light power versus allotment matching request

3.1.6 Crew Atmosphere

The crew atmosphere includes laboratory space, habitat chambers and the IC tunnel air volumes for a total of 34,366 mols of air. The crew and SPS consume oxygen from the atmosphere and release carbon dioxide. Air is sent to the ARS for carbon dioxide scrubbing, where oxygen also is added.

3.1.7 BPC Atmosphere

The BPC atmosphere in the present model has a volume of 16768mols. Plants consume carbon dioxide in the production of carbohydrates, producing oxygen. At the same time, the plants respire oxygen as these carbohydrates are used to build various plant structures. The net carbon fixation is positive in the daylight hours and negative at night. Air from the BPC atmosphere is sent to the ARS for oxygen scrubbing, where carbon dioxide also is added. There is no accommodation made for the addition of oxygen to the BPC atmosphere in the current model.

3.2 Power Relations

At this stage of model development, power relations for a handful of components have been included: the oxygen generator, carbon dioxide scrubber/crew chamber air system, the incinerator, and BPC crop lighting. Processes will have various power demand 'profiles' depending on their operational characteristics (see for example, Weaver, [1999]). Some processes are continuous, and power to them can be varied continuously. Other processes are run in a 'batch' mode. Depending on the details of this type of process, power may be varied either continuously while a batch is being run, or only from one batch to another. These constraints on power profiles will have to be accommodated by the power management system.

3.2.1 Oxygen Generator

The Solid Polymer Electrolysis (SPE) unit is used to supplement the flow of oxygen from the BPC to storage. A control loop determines the desired oxygen production rate and the corresponding rate of water usage. The power the unit draws is a linear function of the flow of water into it. The minimum power draw is 36 Watts. The equation relating flow (Q, in Mols H_2O/Hr) to power (*Watts*) is given by:

$$\frac{Q}{0.006} + 36 = Watts$$

The SPE requires a minimum of 36 Watts power. When power is limited, i.e. when the power manager imposes a power level, the maximum processing flow is determined by the inverse of the above function. The above equation for the SPE is based on data from [Erickson96].

3.2.2 Carbon Dioxide Scrubber

A hydrophobic molecular sieve (4BMS) is used to extract carbon dioxide from the crew air chamber in the model. It has two adsorption/desorption beds and two desiccant beds to prevent water from poisoning the adsorption beds. Only one of the two beds is actively adsorbing carbon dioxide at any given time. The 4BMS is designed to simultaneously adsorb carbon dioxide (active bed) and desorb carbon dioxide (inactive bed).

Incoming air is blown over the active bed, which adsorbs the carbon dioxide from the air. The majority of its power is used to heat the inactive bed. Once the inactive bed is heated to the proper temperature and the carbon dioxide is completely desorbed, the incoming air is then diverted to it, making it the active side. The previously active bed becomes inactive, and is then heated to begin desorbing carbon dioxide into a tank which in turn supplies the BPC. This cycle is repeated within the scrubber and the period is known as the "duty cycle." If the active bed becomes saturated with carbon dioxide, the air will continue to flow past the saturated bed, but no carbon dioxide is adsorbed. This point is referred to as "break through."

The power available to the 4BMS is subject to reduction as the power manager sees fit. A fixed, one-hour duty cycle time is assumed. If power is reduced to the 4BMS, the scrubber blower is turned off, and the heaters for the desorbing bed are turned down in order to keep the beds "warm." Because the 4BMS is no longer adsorbing carbon dioxide, the carbon dioxide levels in the crew atmosphere begin to rise. This "standby" state can be maintained as long as the carbon dioxide level in the crew chamber is within a predefined tolerance. Power is restored as those levels are reached to again begin removing carbon dioxide from the crew chamber. The scrubber is then not subject to having its power reduced until it can complete at least one duty cycle.

The 4BMS capacity has been set to 5000 grams of carbon dioxide adsorbed per duty cycle. The energy required to completely desorb carbon dioxide from the bed corresponds to a power of 3500 Watts applied over the one-hour duty cycle time. The standby mode has a reduced power requirement of 1000 Watts.

The 4BMS is one part of a larger system that removes carbon dioxide from the crew atmosphere. The primary fan or "blower" which forces carbon dioxide rich air from the crew atmosphere through the scrubber is modeled as a constant speed fan. Additional detail including other fans, valves and compressors is not currently modeled.

3.2.3 SPS

The power consumed by the SPS depends on the composition of the waste stream. Since we assume that this composition is constant for gas balance purposes (Section 3.1.2), the power that the SPS consumes nominally will vary with the rate at which the waste must be processed. We use the following linear relationship:

$$pwr\_sps = 5000 + 10000 * waste\_in$$

where *pwr_sps* is given in Watts, and *waste_in* is given in mols per hour.

Greater amounts of water in the stream require higher power to process. We use this as a source of disturbances to the system in testing the power management system performance.

3.2.4 Crop Lights

The crop light power has been treated in the BPC power management section.

3.3 Subsystem Processes

For the purposes of this model, we have identified four subsystems. Each subsystem process involves a combination of components linked in terms of mass flow control and power. A process can include any number or types of components, including buffers, true mass processors such as the crew chamber, and their associated control subsystems. The processes are:

1. The oxygen storage tank and SPE with the oxygen scrubber, and the PID controller monitoring the level of oxygen in the tank.

2. The carbon dioxide storage tank and the incinerator, along with the controller monitoring the level of carbon dioxide in the tank.

3. The crew chamber atmosphere, along with the carbon dioxide scrubber. A PID controller monitors the level of oxygen in the crew air and draws from the oxygen storage tank as necessary. Carbon dioxide levels in the crew chamber are monitored, but there is no continuous control loop around this measure. The crew chamber fan sending air to the carbon dioxide scrubber is either off or on. The fan and the carbon dioxide scrubber are sized to accommodate fluctuations in level of carbon dioxide. If the level of carbon dioxide in the crew chamber exceeds a preset value, the fan is turned on and air is sent to the 4BMS.

4. The BPC atmosphere and the crop lights. Two controllers monitor the crop atmosphere. One of these adjust level of carbon dioxide in the atmosphere, the other determines the rate at which crop air is sent to the ARS to be scrubbed of oxygen.

Tolerance levels for each processor are given in Table 3. In the current model, the tolerance limits are single-sided, meaning we are concerned only with lower or upper range limitations on the system state, depending on the process.

Table 3. Process setpoints and tolerances

Process	Setpoint	Tolerance constraint[1]
O_2 tank and SPE	500 mols O_2	Setpoint - 100 mols O_2

CO_2 tank and incinerator	500 mols CO_2	Setpoint - 50 mols CO_2
Crew atmosphere and scrubber	7904 mols O_2 (23%) (no setpoint for CO_2) 26452 mols N_2 (76.97%)	Setpoint - 100 mols O_2 ≤12.3 mols CO_2 (0.032%) (constant, no leakage)
BPC atmosphere and lights	3857 mols O_2 (23%) 16.8 mols CO_2 (0.1%) 12895 mols N_2 (76.9%)	Setpoint + 100 mols O_2 Setpoint - 100 mols CO_2 (constant, no leakage)

Notes: 1. The tolerance constraint is set individually for each process. If the process controller has been circumvented by the power manager, control is reverted to the process controller when the state reaches the tolerance constraint. The carbon dioxide and oxygen tanks currently have no upper size limit.

4 Power Management

The fundamental challenge of power management is to both use power efficiently (reduce the demand for power) and avoid surges that exceed power plant capacity, without sacrificing life support function. The work thus far concentrates on reducing the necessary system power plant capacity through management of power surges. Ideally, one would like to avoid excess demand in the first place. Thus one may have individual processors modify their power demands in response to overall system power availability and the collective demand for power. "Demand-side" management involves deciding how the collective demand and/or total power available affects individual processor demand. At the core of both surge and demand-side management is the use of tolerance bounds on life support function. Without the flexibility to operate within a range, surges could not be managed and individual demand could never be modified.

Both surge and demand-side management require some measure of coordination between processes. This coordination can be direct in nature, as in the case of a high level system controller giving commands to subsystem managers, or indirect, as in the case of subsystems exchanging resources through the intermediary of a market. We have implemented the current power management scheme as a hierarchy of controllers in which stasis is maintained through setpoint control at the process level, while a higher level controller manages power. The power manager gives processes what their individual PID controllers demand, without any further regard to overall power usage, unless total power demand exceeds total available power.

We adopt a hierarchy because it is unlikely that power management will be implemented in either an exclusively centralized or distributed manner. A centralized management system, while potentially efficient in power use, is not robust to failure. Furthermore, a centralized scheme would require coordination of huge amounts of measurement data, and likely would require intensive computation. Both requirements may be in excess of current processing capabilities. A truly distributed management approach, while avoiding the problems of communication and computation, could not be implemented since some level of coordination of subsystem power demands is required to meet life support goals under limited power availability. Unless the result is consistent with the common good, subsystems can not operate in their self-interests alone.

The research described here is a first step toward the power management challenge. As currently implemented, a high level controller intervenes at the process level directly when total power demand exceeds supply. The subsystem controllers do not take into account global power availability in setting their demands, but are coordinated through the higher level management system. Thus the subsystem control strategies remains simple, for the most part independent of the global power management strategy. The approach has the flexibility to allow for future additions and modifications as research progresses. In particular, the hierarchical structure adopted can be modified to accommodate a market approach to demand-side management. In this scenario, the high level controller described below would be replaced by an algorithmic implementation of a market, and subsystem controllers would be designed to interact through this market.

4.1 The power manager

Power manager takes process requests for power and determines power allotment. If process requests exceed supply of power, some processes must be shut down or power to them reduced. In order to realize this power management scheme, it is necessary to determine acceptable operating ranges or tolerances for individual processes. This tolerance is understood to represent acceptable limits within which a process can be operated, without risk to the safety and comfort of the crew and overall life support function. The tolerances provide the margin necessary to share power when attempting to avoid exceeding power supply capacity. This underscores the need to design ALS subsystems with a certain amount of operational flexibility in order to maintain system integrity under dynamic loads on power and mass flows.

When a process is within tolerance, it is eligible to have its power reduced by the power manager. The power manager effectively takes control of the process level. If power is not restored before the tolerance limit is reached, the process becomes critical and must have its power (i.e. control) restored. Power must then be claimed from one or more additional processes, or the total system power supplied by the power plant must be increased.

In the current model, the power manager polls the processes in a synchronous manner, with a fixed time step (every 12 minutes). Processes submit power requests at every time step and receive an allotment based on their previous requests. Power remains fixed between these sample times. In implementing the power manager, an asynchronous scheme could be used as processes may be turning on and off on individual schedules or signals. However, with a short sample time a synchronous scheme works well.

4.1.1 The Power 'Auction'

When the power manager determines that the total power demand exceeds a preset level, the power management 'auction' is initiated. The manager polls the processes in order to determine which is available for the auction. The determination of eligibility for the auction is discussed in section 4.2.2. Among those processes eligible for the auction, each supplies the manager with a measure of its current satisfaction of its tolerance settings, normalized to a scale of zero to two. A measure of one means the process state is currently meeting its setpoint goal; a measure of zero means that the process state is at its critical tolerance limit; and a measure of two means the process state is 'far' from the critical tolerance. Currently, we saturate the measure away from criticality at two, and assume that no danger arises when the measure is near or greater than two. An example of a satisfaction measure and the corresponding tank level is shown in Figure 10. Other process operational restrictions, such as batch mode operation (which requires full power during the 'on' phase), can be easily accommodated because the individual processes set their eligibility.

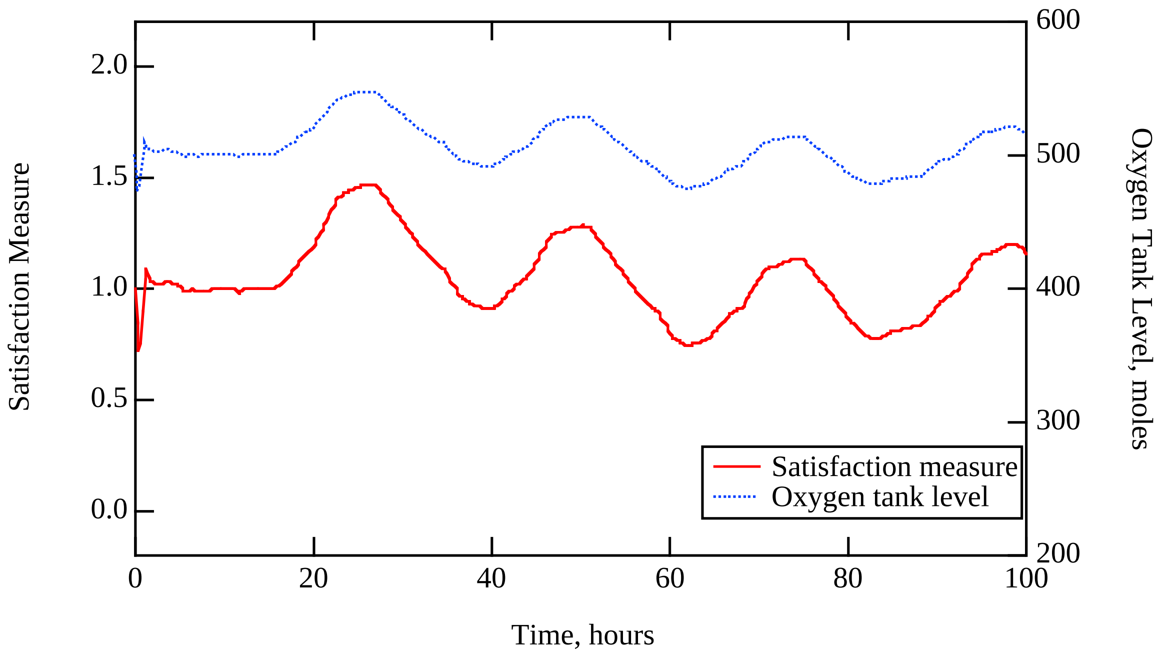

Figure 10. Oxygen Tank Level and corresponding Satisfaction measure for SPE

To decide the order in which eligible processes will have their power reduced, the satisfaction measures are weighted and compared to one another. The weight associated with each process are, at this time, fairly arbitrary. However, the advantage to using weighted satisfaction measures as opposed to just the satisfaction measures themselves is the ability to assign relative priority, a priori. Some subsystems may be more sensitive than others to volatile processor states with respect to their nominal condition. Similarly, certain processors may be more adversely impacted than others by having their power frequently reduced. The lower the weight, the more problematic it is for that subsystem to have its power reduced and therefore, as a result of it being assigned a lower weight, the less likely it is to be cut. We multiply the weights by the respective satisfaction measures, and order the products from highest to lowest. Those processes whose power one would like to reduce later rather than sooner have a lower weighted satisfaction measure. Figure 11 shows the set of weights chosen for our model and the weighted satisfaction measures for a particular seventy-two hour period. When the power manager decides that something needs to be "cut," it will start with the process that has the highest weighted satisfaction measure, and if needed, move to the process with the next highest and so on.

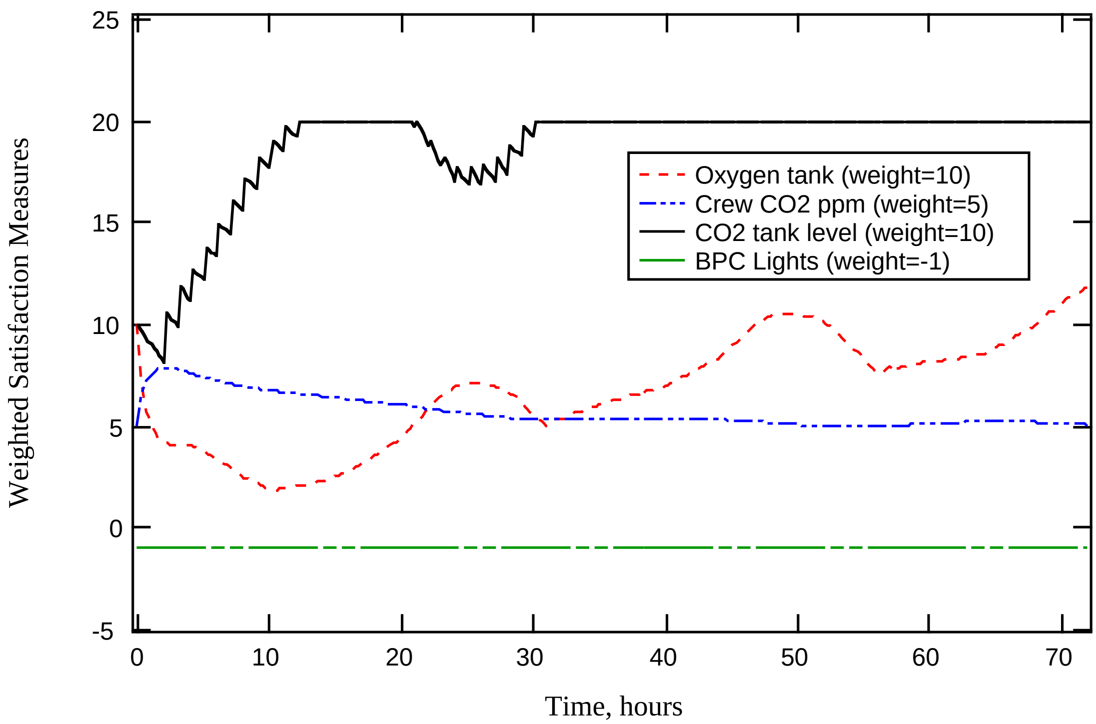

Figure 11. Weighted Satisfaction Measures used to determine priority

The BPC lights do not have a setpoint they are maintaining, however using the BPC power smoothing strategy as described in section 3.1.5, the crop trays will always meet their respective target average PPF levels over a given photoperiod. Therefore, the satisfaction measure is continually set at one. For our model, the lights have arbitrarily been determined to have the highest relative priority, and should therefore only have their power reduced after all other eligible processes are cut and there is still a need for further power reduction. They are assigned a weight of negative one to ensure that they will always be the last process to be cut.

This form of 'auction' possesses practically all of the functionality of a market, in which the ability of a process to receive power is a function of its 'wealth.' Those processes which are more critical will have greater 'wealth', and will be able to 'buy' their way out of power 'poverty.' Under a market-based management strategy, the power delivered to processes is a function of both supply and demand, and will vary from one auction to another. Thus the present management architecture can be expanded quite easily to include market-based or other strategies to modify power demand (demand-side management) as well as limiting power delivered (surge protection).

In the current implementation, the power to a process is reduced a fixed (*a priori*) amount, except for the crop lights, whose power can be reduced in discrete levels of 1000 Watts. Power is cut one process at a time until the total power demand no longer exceeds the supply limit. Power to the crop lights is reduced if and only if all other eligible processes have had their power reduced and power needs to be reduced further. Once a processor's power has been reduced, the process state is allowed to drift within its tolerance range. Power to a process is not restored until the tolerance limit has been reached, at which time the process becomes 'critical'.

4.2 Process Controllers

Setpoint control in the current BIO-Plex air-loop model is effected through the use of PID feedback control around individual processors and subsystems. The model currently possesses five PID controllers:

1. One PID controller monitoring the level of oxygen in the oxygen storage tank. It determines the rate at which water is processed to produce oxygen.
2. One PID controller monitoring the level of carbon dioxide in the carbon dioxide storage tank. It determines the rate at which waste is processed by the SPS to produce carbon dioxide.
3. One PID controller monitoring the crew atmosphere. This controller maintains the oxygen level by transferring oxygen from the oxygen storage tank.
4. Two PID controllers monitoring the BPC atmosphere. One of these maintains the carbon dioxide level by transferring carbon dioxide from storage. The other PID controller monitors the oxygen level in the BPC atmosphere. It determines the rate at which BPC air is sent to the ARS in order to be scrubbed of oxygen.

Our approach to power management requires several modifications to the traditional PID algorithm function. Primary among these, the PID must know what to do when power to the process it is controlling is reduced (as part of a global power management strategy), and be able to communicate to the higher control level when additional power is required to avoid exceeding the operational tolerance.

4.2.1 Bumpless Transfer

When the global management level decides power to one or more processes must be reduced, a signal switches individual PID controllers off as necessary. In the off state, a PID controller supplies no signal. Instead, the high-level component of the power management system determines the power to the process, as described above. This causes the state of the affected processes to drift, since no direct feedback is present. When a process state reaches its predefined tolerance, PID control is restored. The process is no longer subject to having its power cut until its state is reaches a pre-defined neighborhood of the original set point.

While the current process controllers try to achieve a given setpoint, the nature of the tolerances is such that any behavior within tolerance is acceptable. We take advantage of this fact in modifying the setpoint slightly as necessary.

As PID controller(s) come on-line after having their power restored, precautions must be taken so as to avoid aggressive control signals, which may cause further surges. For example, consider Figure 12, which shows the response of the oxygen tank over the course of two days. The SPE is shut down approximately three hours into the day to counter the presence of a surge in total power. At approximately twelve hours into the first day, the oxygen tank reaches its tolerance and power to the SPE is restored. The power required to achieve the response in Figure 12 is shown in Figure 13, using the power relation given above. Clearly, it is unnecessary to restore the oxygen tank level so quickly, given that any level within tolerance is acceptable. A recovery strategy that demands less power would be useful.

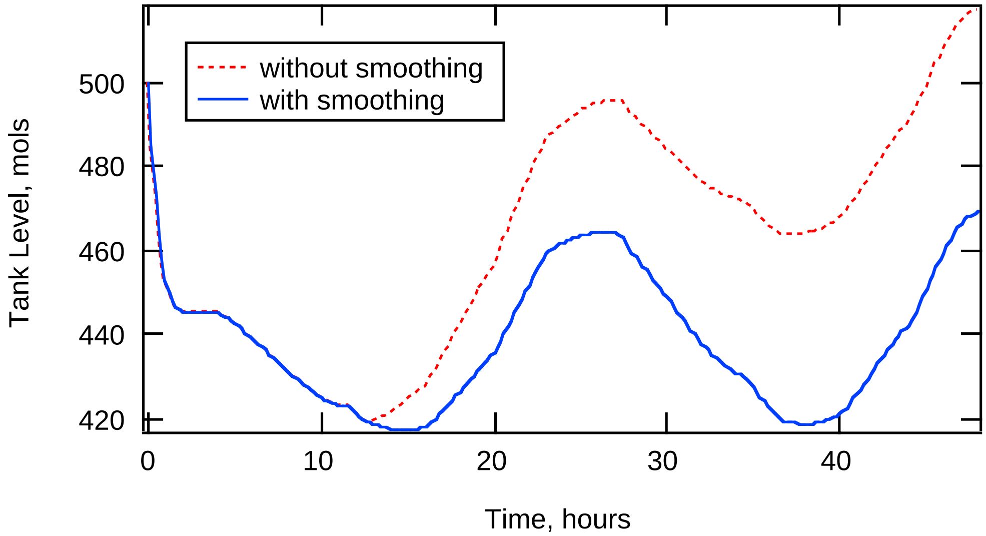

Figure 12. Oxygen tank level with and without setpoint smoothing

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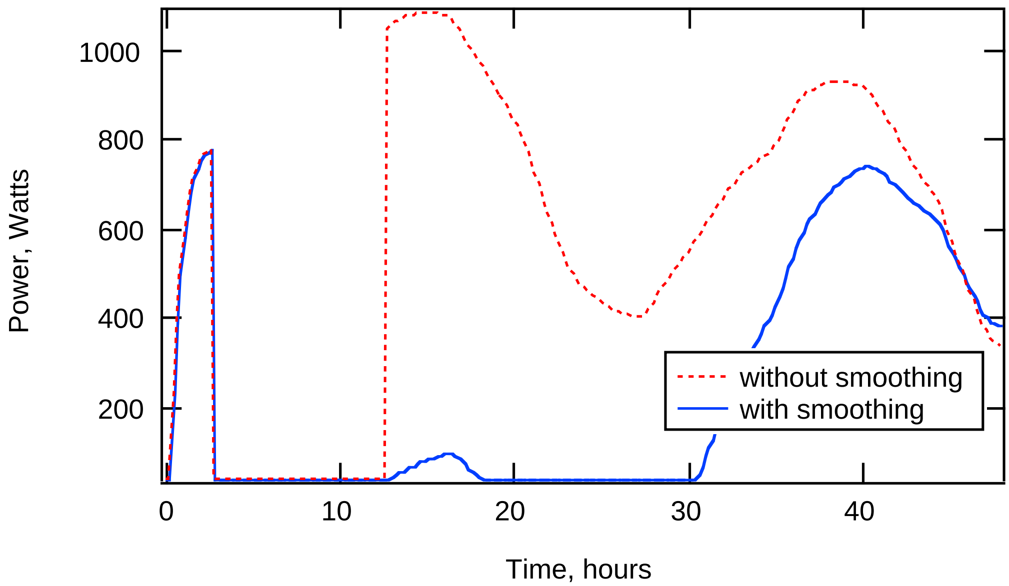

Figure 13. SPE power consumption with and without setpoint smooting

One way to reduce the demand for power is to carefully tune the controller gains. However, control performance may be compromised. Therefore, the strategy adopted is to modify the set point of individual controllers as they come on-line. In the current simulation, the setpoint is the output of a dynamic system, thus moving along a predetermined trajectory beginning at the current process state (the tolerance limit), and ending at the nominal set point. The exact shape of the trajectory and the motion along it can be specified as necessary. Since it is assumed that operation within tolerance is acceptable, the processor operation is not limited to set point type behavior. Although we have chosen to do so, it is not unlikely that some other default operation will be deemed beneficial upon restoration of power to the process. The nominal setpoint in the example developed here is 500 Mols oxygen, and controller gains are unchanged from one simulation to the next.

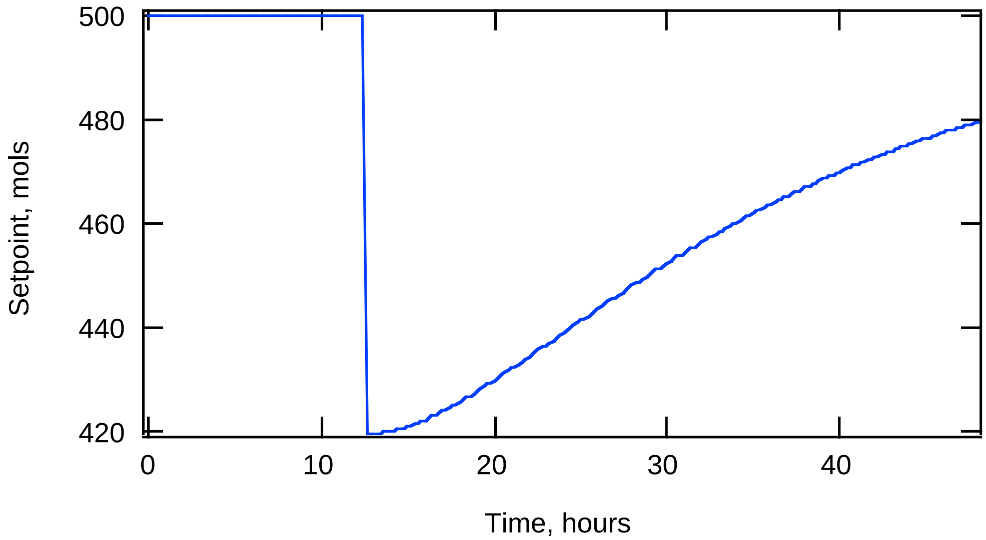

Figure 14. Smoothed setpoint, oxygen tank

In the current model, the set point dynamics can be either first or second order. The setpoint trajectory (with second order dynamics) for the example developed here is shown in Figure 14

4.2.2 Signals to the Power Manager

Each PID sends two signals to the power manager. The first is a normalized measure of the current state of tolerance constraint satisfaction, i.e. the processor’s satisfaction measure as discussed in section 4.1.1. The other indicates to the power manager whether or not the process is eligible for the power auction. These signals are calculated in the following manner.

Every process state has a direction in which it will drift under low-power conditions. For single state processes these are described generically as “up” and “down”. For “up” drifting systems, the tolerance location signal is given by:

$$\frac{((setpoint + \Delta x) - x)}{\Delta x}$$

where x is the process state, *setpoint* is the setpoint and Δx is the tolerance about the setpoint (assumed to be centered about the setpoint).

For "down" drifting systems, the tolerance location signal is given by:

$$\frac{(x - (setpoint - \Delta x))}{\Delta x}$$

Figure 15 shows the location signal for the oxygen tank in the example developed here. Recall that this value is normalized to be between zero and two. Notice that its shape is isomorphic to that of the tank response, as expected. The case with no smoothing reaches the nominal setpoint, which has a normalized value of one. The location value is weighted and used to decide which processes are to have their power cut, as described above. The higher the product of tolerance location and weight, the more likely the power will be cut.

Eligibility for the auction is determined by monitoring the difference $(x - setpoint)$ for "up" systems and $(setpoint - x)$ for "down" systems. When this difference reaches a neighborhood of the tolerance bound (given by $(\Delta x - \varepsilon_1)$), the process is no longer eligible for the power auction. It remains ineligible for the auction until this difference reaches a neighborhood of zero.

Figure 16 shows the tolerance flag for the oxygen tank controller in the example developed here. Notice that, in the case with no smoothing of the setpoint, the SPE becomes eligible for another auction at the end of the first day since the tank level returns to (albeit briefly) the nominal setpoint. In the case of setpoint smoothing, the SPE is not eligible for further power cuts since the tank level has not yet attained the nominal setpoint.

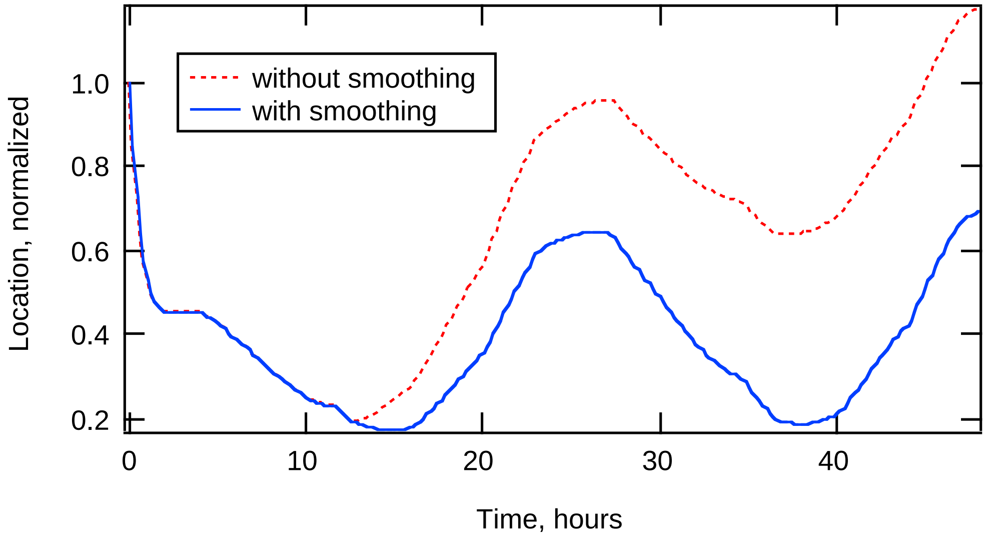

Figure 15. Location within tolerance, oxygen tank

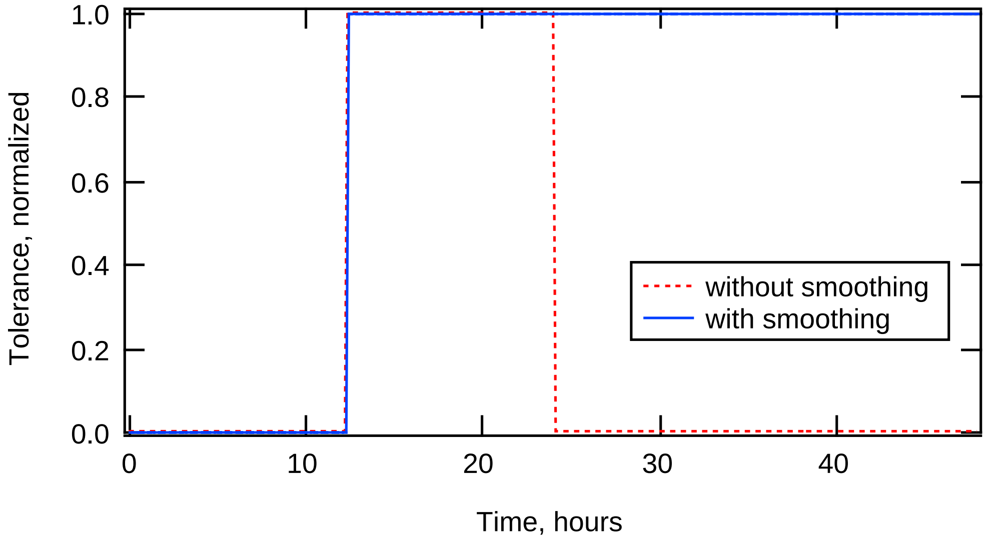

Figure 16. Tolerance flag, oxygen tank

5 Results

5.1 The Effects of Poor Scheduling

In this section, we examine the repercussions of poor scheduling on total system power use. We use the planting schedule of case 1 (Table 2, Section 3.1.5). In contrast to the examples of that section, here the BPC must operate within the limitations of the entire system. Thus in most of the cases presented here, the power allotted to the BPC reflects its power demand, the requirements of the other processes, and the total available power.

Case 1 no power management

In case 1 we examine the total power under no power management. Figure 17 shows the time history of power consumption for two processes (the oxygen tank/SPE and the BPC), and the total system consumption (all four processes). The other processes are at constant power. The SPE turns on near the beginning of the first day in order to make up for losses in the oxygen tank (see Figure 20). The maximum power usage is approximately 235 kW.

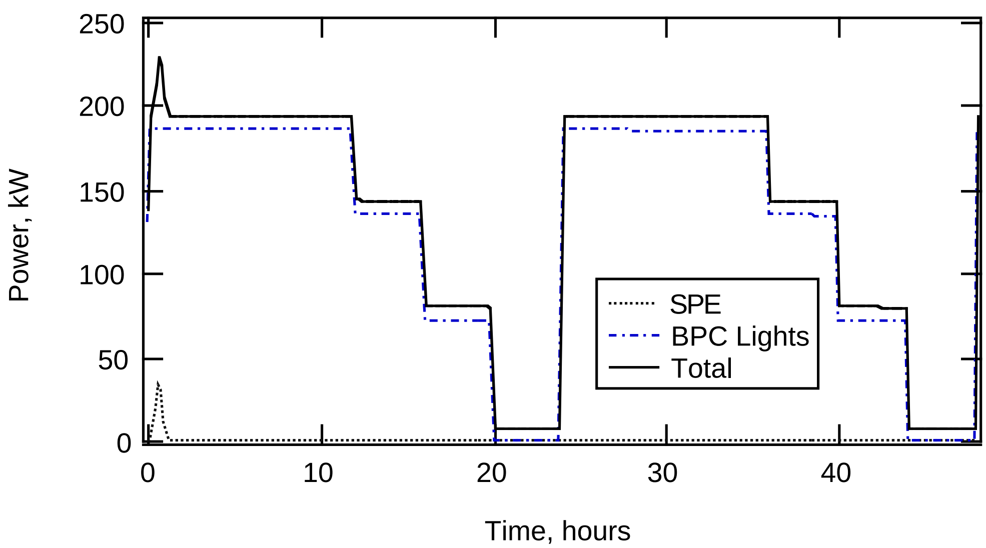

Figure 17. System power under no power management

Case 2 limit = 150 kW

In case two, the power management system is in place, and attempts to limit total power consumption to 150kW. Figure 18 shows the results. The power manager attempts to limit power to 150kW, but is unsuccessful. It cuts the power to all processes, but the lights and the crew air periodically become critical. The power to SPE is cut, but the oxygen tank level does not go critical, meaning that the level of oxygen in the storage tank remains within the tolerance constraint (Figure 20). The power manager takes advantage of the fact that in case 1 the SPE need not have been turned on in order to save power and deliver it to the BPC lights instead. It is easy to see when crop trays in the BPC require more light – there is a major jump to over 200 kW in power consumption. The crew air power consumption is smaller relative to that of the lights, but one can see a slight ripple in the total power when the crew air carbon dioxide level comes in and out of tolerance as the power auction proceeds (see Figure 21). The ripple is due to the fan and carbon dioxide scrubber receiving full power as necessary.

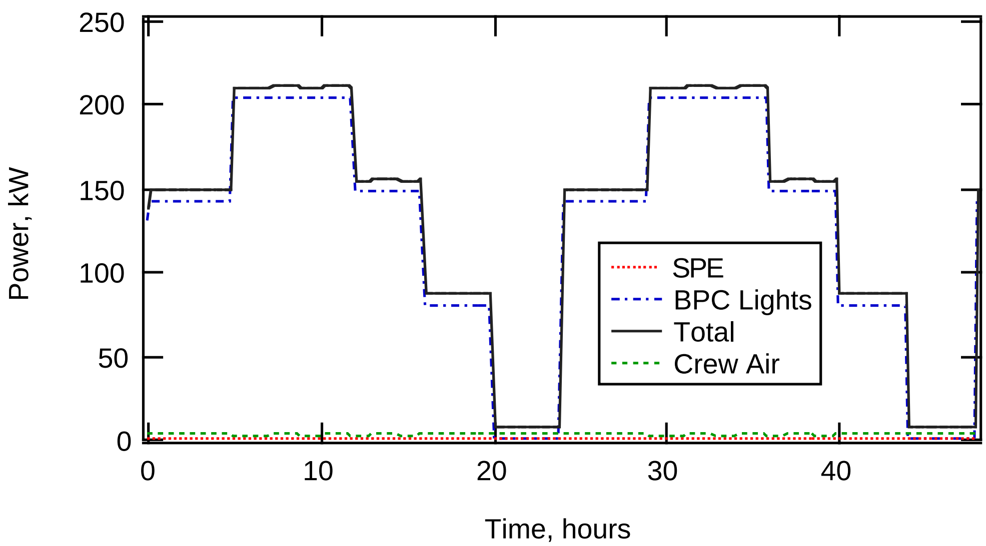

Figure 18. System power under power management, limit = 150 kW

Case 3 limit = 187 kW

In case three, the power manager attempts to limit total system power consumption to 187 kW. This number, determined by trial and error, is the lowest total power level that does not cause the crop trays to go critical. In comparison to case 1 therefore, we have significantly reduced the size of the required power plant (by approximately 38 kW). Note that in case 3, as in case 2, both the SPE and the crew air processes have their power cut. The oxygen tank level differs between the two cases because the light levels between the two examples are different, thus changing the oxygen production of the plants (see Figure 20). Similarly, the crew carbon dioxide level is different from that of case two (see Figure 21). Because light power usage is not as restricted as it is in case 2, there are times at which no crop trays are critical. During these times, the power to the other processes, including the crew air, does not need to be cut. Consequently, the crew air carbon dioxide level is slightly smoother in case 3 than in case 2 (see Figure 21). The plateaus in the total power are flat because the total power level of 187 kW is just adequate to meet the system needs. In case 2 the total power shows ripples just at those times during which extra power (above 150 kW) was required to meet system power requirements.

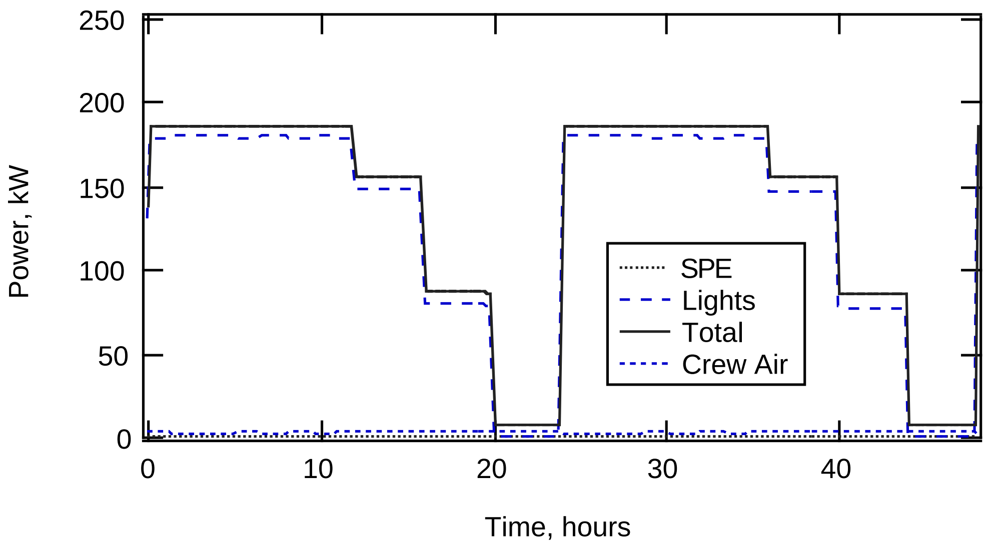

Figure 19. System power under power management, limit = 187 kW

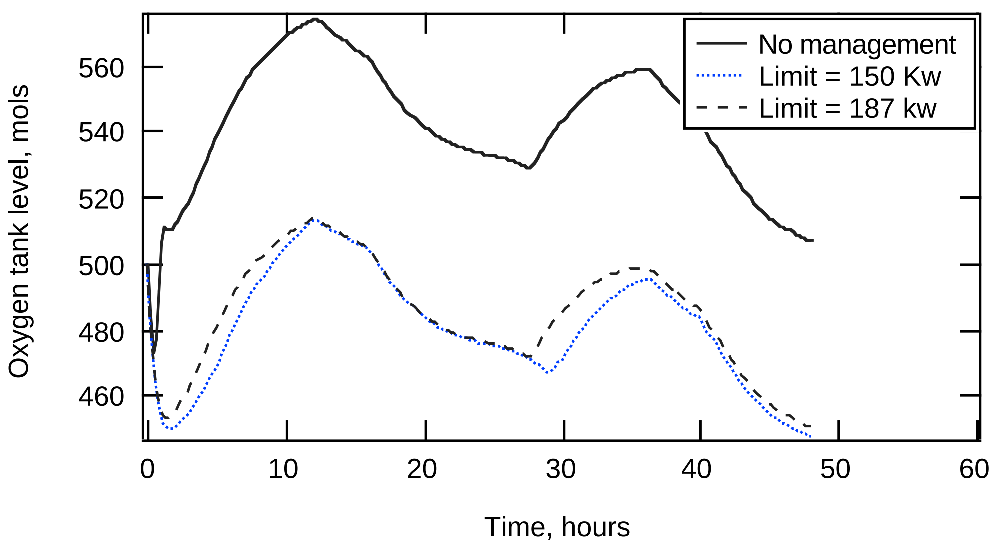

Figure 20. Oxygen tank response

While the power management system described here offers some benefits, the fundamental conclusion that must be drawn from these experiments is that poor scheduling of crop planting has serious repercussions on system power consumption (as well as gas balance). In order to fully capitalize on any power sharing strategy, whether dealing with surge management as has been done here, or a more sophisticated demand-side approach, there must be a balanced number of both sinks and "sources" of power. If the major power consumers (BPC lights in this case) are all on or off at the same time, little sharing can occur under any strategy.

The next section will demonstrate the energy benefits of a better crop planting schedule.

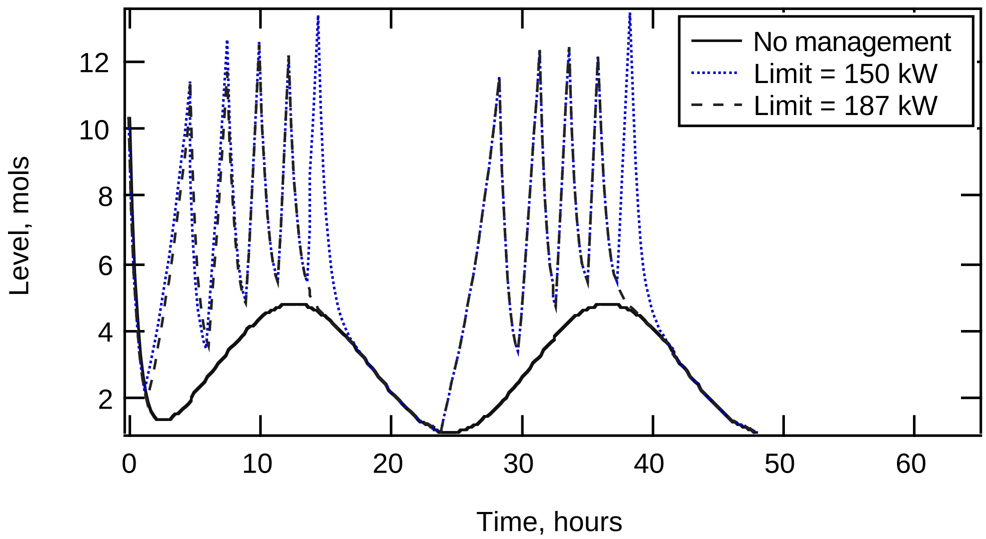

Figure 21. Crew chamber carbon dioxide level

5.2 Disturbance Rejection

In this section we will investigate operation of the model under the "balanced" planting scheme of cases 2 and 3, section 3.1.5 (refer to Table 2), both with and without disturbances. Figure 22 shows the "baseline" result of running the system for one day, both with and without the power manager limiting system power to 155 kW. . The improved planting schedule lessens the dips in power consumption, but the power manager still must intervene just after midnight and at approximately 4pm in order to avoid exceeding 155 kW total power.

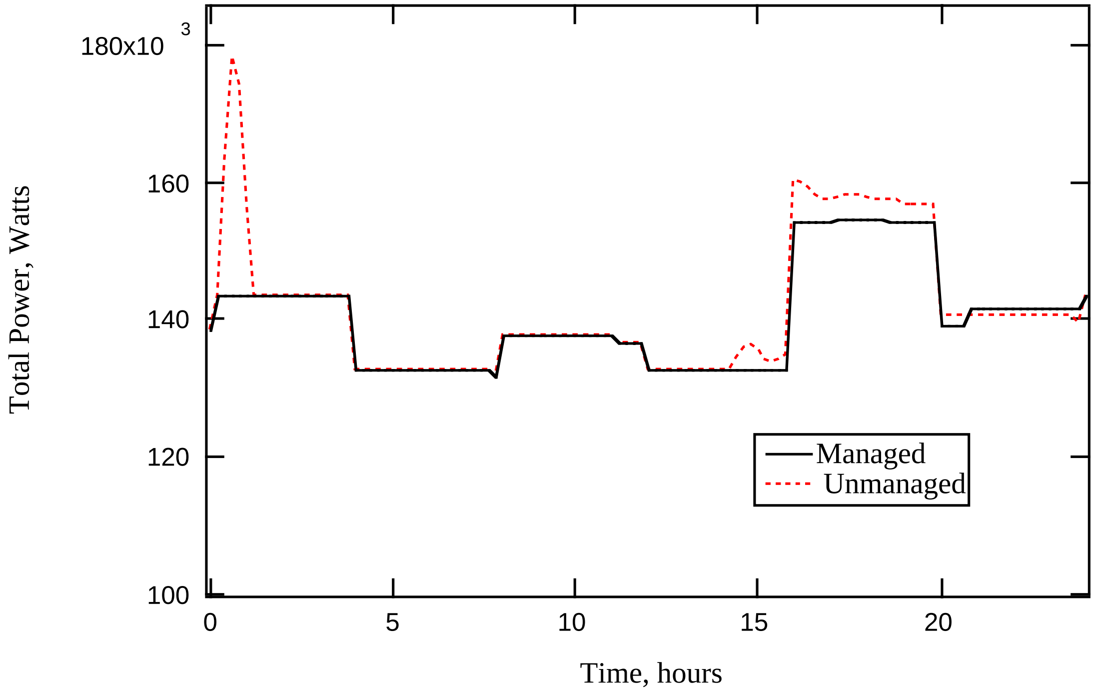

Figure 22. Total power, baseline

We hope to show that improved scheduling not only smoothes power usage, but that it provides the system with enough flexibility in managing power to deal with disturbances. Here we consider the power usage of the crew chamber in addition to the power consumption of the subsystems already discussed. In the baseline case, we allot 5 kW as part of the total system consumption of 155kW. This 5 kW is a minimal power level as estimated in [Weaver, 1999]. Over the course of the day, crew activity produces a power consumption profile as in Figure 23 [Weaver,1999]. The level above 5 kW we consider to be a disturbance. We assume that this represents equipment that has no effect on mass balances being used.

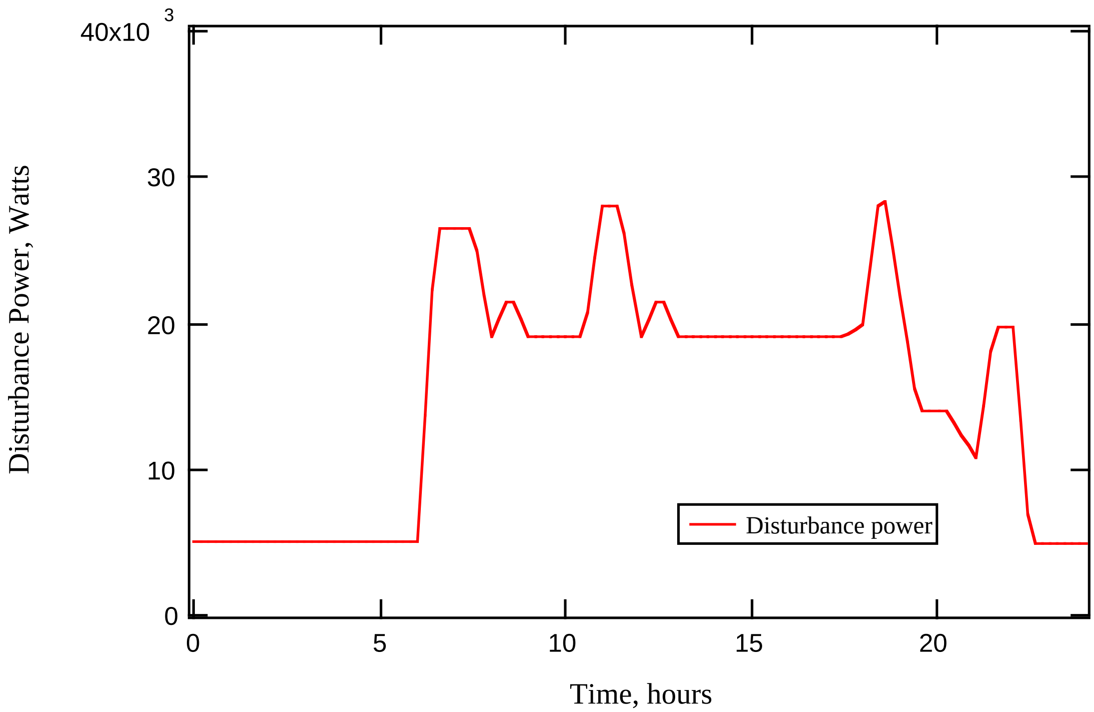

Figure 23. Disturbance, crew chamber

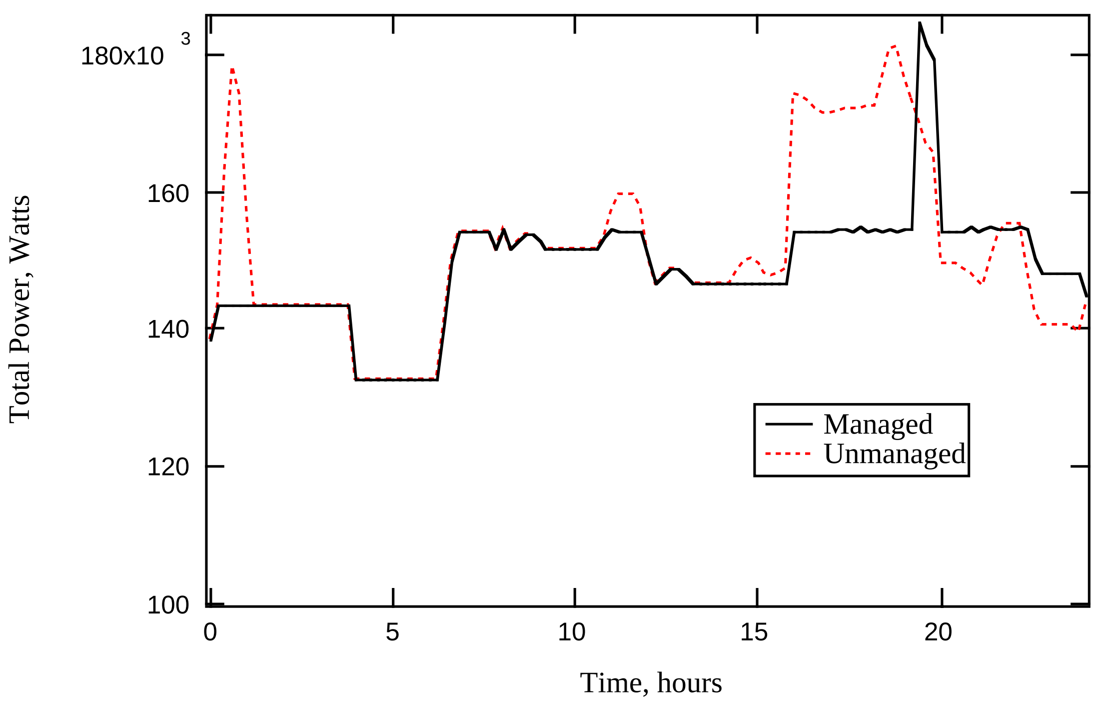

Figure 24. Total power, with disturbance, limit = 155kW

Figure 24 shows the system response with the crew disturbance in place, both with and without power management. Power is still limited to 155 kW. In this case the level of

155kW appears to be too low to absorb the disturbance, as under power management this level cannot be maintained. One strategy to overcome this problem thus would be to increase the total power level. However, the power usage profile indicates that there are significant periods in which the system does not utilize the full capacity of the power supply (155kW). Therefore a better allotment strategy during these times may be enough to meet the power limit at other times.

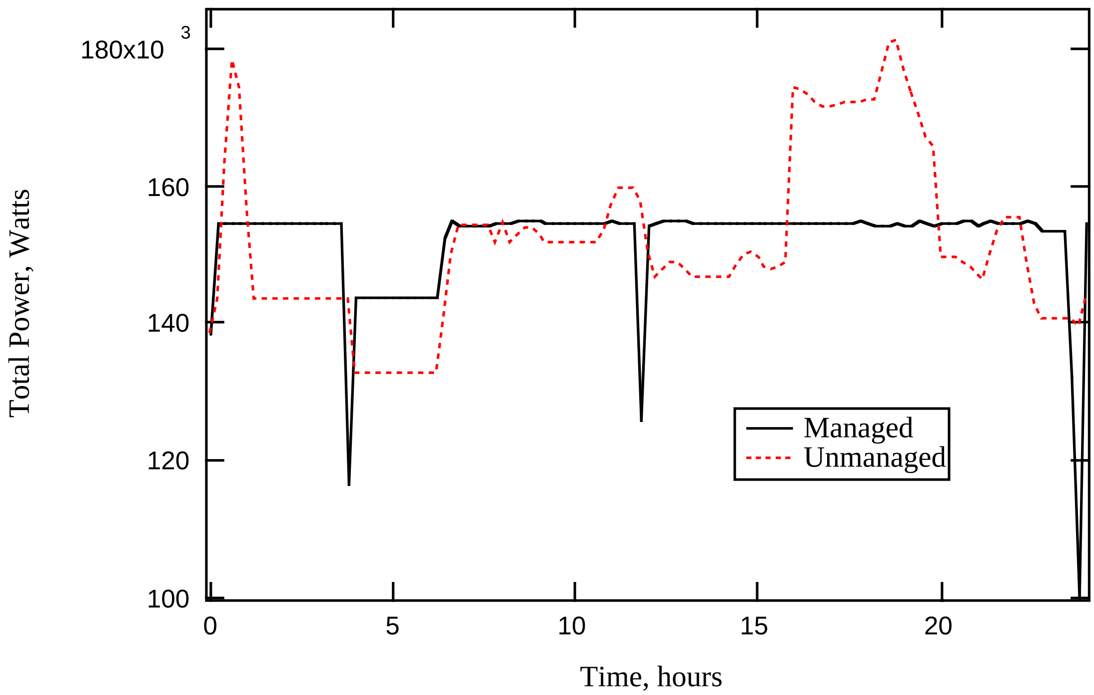

Figure 25. Total power, with disturbance, new BPC strategy, limit = 155kW

Since the lights are responsible for the violation of the limit on power, we will attempt to improve the strategy for power allotment to the BPC. Currently, the BPC is allotted only as much power as it requests. However, as results of section 3.1.5 show, the BPC can use more power than it asks for. Therefore, our strategy will be to deliver more power than required by the BPC during those times when the system is under-exploiting its power plant. Because the BPC attempts to meet *daily* targets, this excess power will reduce the overall BPC power demand at later times in the day. Figure 25 shows the result of doing this. By allotting more power to the BPC at those times in the day when there is extra power available, we avoid reaching criticality later in the day and can meet the overall system power limitation of 155kW. In fact, the BPC at times must shut down crop trays, ergo the dips in the total power. The total power limit can be reduced to 150kW.

6 Future Work

Future work will concentrate on increasing the effectiveness of the power manager, ultimately moving toward addressing the problem of demand-side power management. This may be addressed by incorporating a general resource management strategy through some form of market-based control or other strategy. Year two will see greater effort put into further investigation of management strategies. In this regard, the approach adopted to date is flexible enough to accommodate further development of management strategies since these will also take the form of a hierarchy (see introduction of section 4). In the case of a market approach, individual processes will submit demands and offers to a central market, which will set prices for goods and keep track of exchanges. While individual subsystems will decide on quantities, the feedback of the prices as set through the central market will have the effect of adjusting demand, or more precisely, the satisfaction of demand. The system described here already has the architecture for such an approach in place. Furthermore, it supplies an overlay for surge management under future power sharing scenarios.

In the upcoming two years of this NRA, we plan to extend simulation work from the first year by expanding the mass flow model to include other life support subsystems. We also plan to test the dynamic resource allocation controller on a real-world application, an existing life support test bed at Ames Research Center. Specific tasks for the second and third year include:

Develop simulation models for other life support subsystems, using the JSC ALS Systems Integrated Test Bed as a baseline system.

Expand the controller to satisfy the resource allocation objectives identified above for the new subsystems.

Prepare a report and/or research paper to document the development and performance of the dynamic resource allocation control system.

Identify a set of resource allocation objectives for the ARC Lab-Scale CELSS Tesbed.

Develop a simulation model of the ARC Lab-Scale CELSS Testbed.

Build a real-time controller to satisfy the resource allocation objectives ientified above for the Lab_Scale CELSS Testbed.

Prepare a report and/or research paper to document the performance of the dynamic resource allocation control system for the Lab_Scale CELSS Testbed.

7 Appendix

7.1 Acronyms

4BMS	Four Bed Molecular Sieve
ALS	Advanced Life Support System
ARS	Air Revitalization System
BPC	Biomass Production Chamber
SPS	Solids Processing System

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